Physics of Gamma-Ray Bursts

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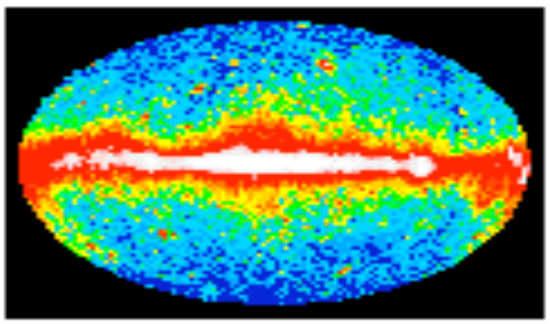
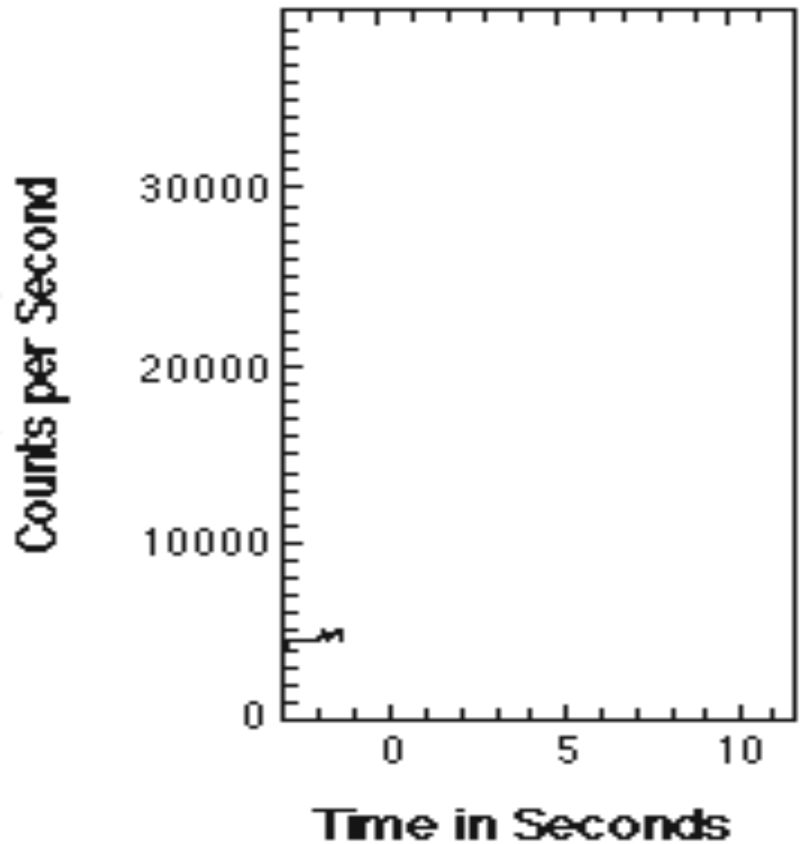
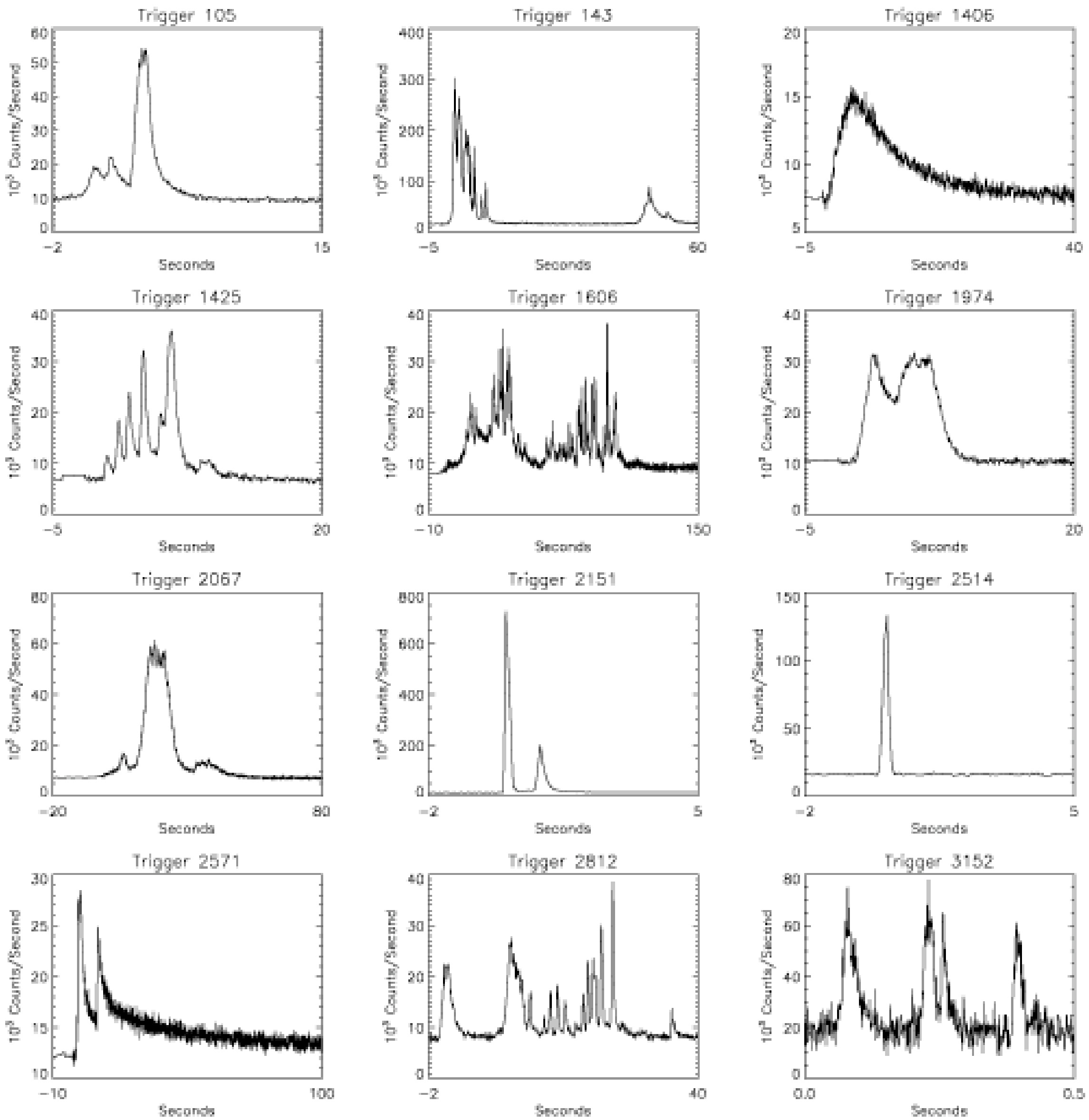
XII Mexican Workshop on Particles and Fields
Mazatlan, Mexico
Nov. 13, 2009

Bursts of Gamma-rays from Heaven

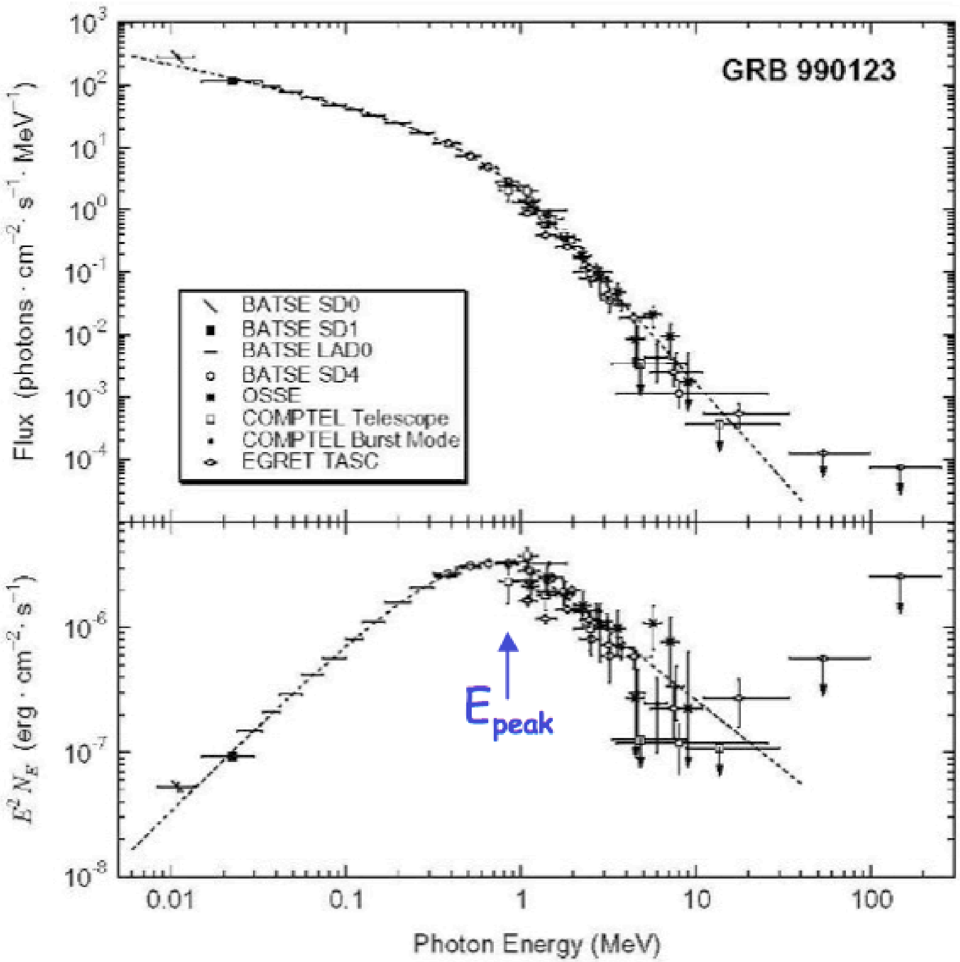




Irregular light Curves



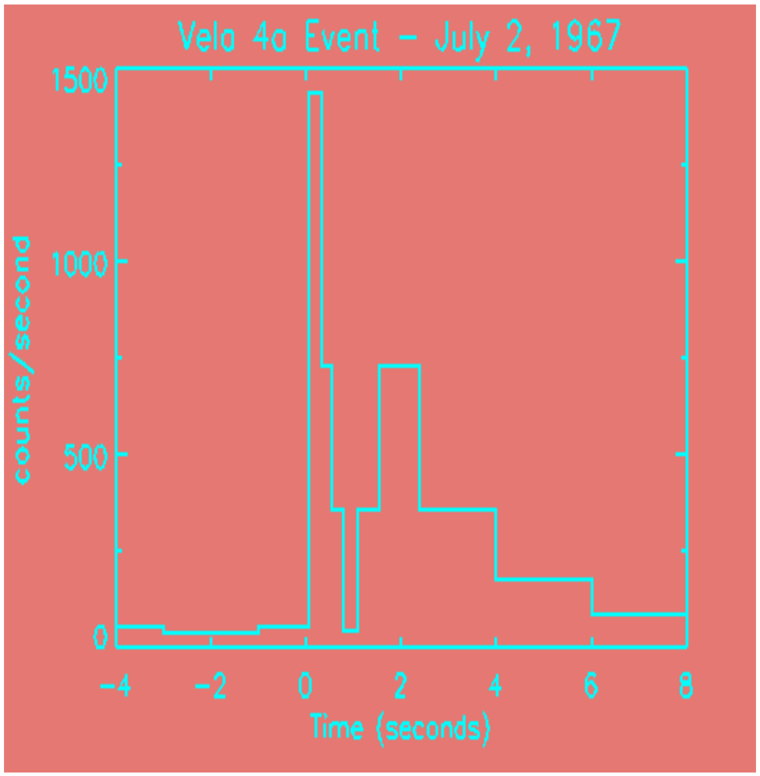
Non-thermal, smoothly joint broken power law spectrum



Briggs et al. 1999

Stage 1: 1969 (1973) - 1990

(discovery and "dark" era)



THE ASTROPHYSICAL JOURNAL, 182:L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

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Received 1973 March 16; revised 1973 April 2

ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

Subject headings: gamma rays — X-rays — variable stars

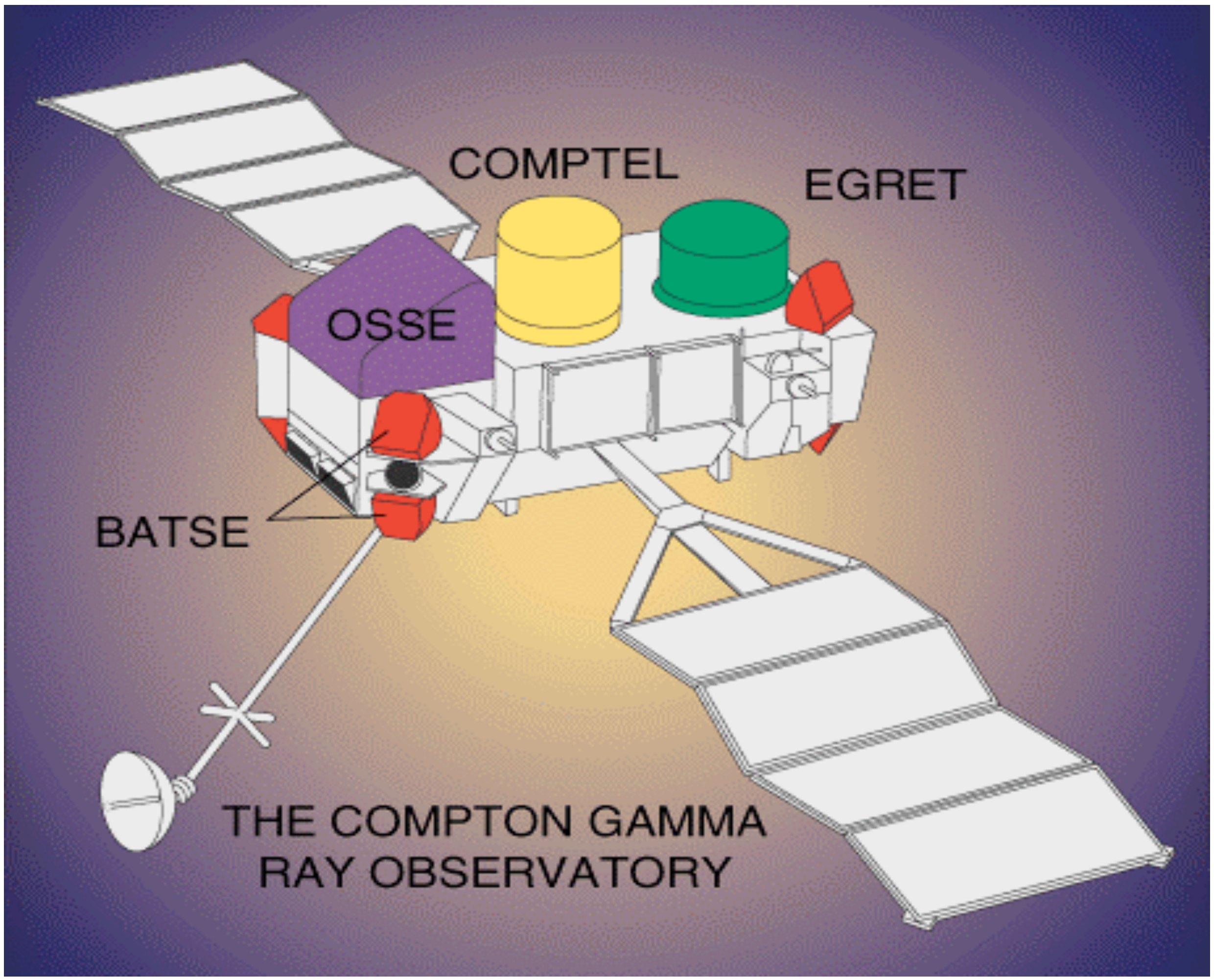
By mid 90's: > 118 different theoretical models !
A theorist's heaven or hell?

Table 1

#	Author	Year Pub	Reference	Main Body	2nd Body	Place	Description
1.	Colgate	1968	CJPhys, 46, S476	ST		COS	SN shocks stellar surface in distant galaxy
2.	Colgate	1974	ApJ, 187, 333	ST		COS	Type II SN shock brem, inv Comp scat at stellar surface
3.	Stecker et al.	1973	Nature, 245, PS70	ST		DISK	Stellar superflare from nearby star
4.	Stecker et al.	1973	Nature, 245, PS70	WD		DISK	Superflare from nearby WD
5.	Harwit et al.	1973	ApJ, 186, L37	NS	COM	DISK	Relic comet perturbed to collide with old galactic NS
6.	Lamb et al.	1973	Nature, 246, PS52	WD	ST	DISK	Accretion onto WD from flare in companion
7.	Lamb et al.	1973	Nature, 246, PS52	NS	ST	DISK	Accretion onto NS from flare in companion
8.	Lamb et al.	1973	Nature, 246, PS52	BH	ST	DISK	Accretion onto BH from flare in companion
9.	Zwicky	1974	Ap & SS, 28, 111	NS		HALO	NS chunk contained by external pressure escapes, explodes
10.	Grindlay et al.	1974	ApJ, 187, L93	DG		SOL	Relativistic iron dust grain up-scatters solar radiation
11.	Brecher et al.	1974	ApJ, 187, L97	ST		DISK	Directed stellar flare on nearby star
12.	Schlovskii	1974	SovAstron, 18, 390	WD	COM	DISK	Comet from system's cloud strikes WD
13.	Schlovskii	1974	SovAstron, 18, 390	NS	COM	DISK	Comet from system's cloud strikes NS
14.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	ST		COS	Absorption of neutrino emission from SN in stellar envelope
15.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	ST	SN	COS	Thermal emission when small star heated by SN shock wave
16.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	NS		COS	Ejected matter from NS explodes
17.	Pacini et al.	1974	Nature, 251, 399	NS		DISK	NS crustal starquake glitch; should time coincide with GRB
18.	Narlikar et al.	1974	Nature, 251, 590	WH		COS	White hole emits spectrum that softens with time
19.	Tsygan	1975	A&A, 44, 21	NS		HALO	NS corequake excites vibrations, changing E & B fields
20.	Chanmugam	1974	ApJ, 193, L75	WD		DISK	Convection inside WD with high B field produces flare
21.	Prilutski et al.	1975	Ap & SS, 34, 395	AGN	ST	COS	Collapse of supermassive body in nucleus of active galaxy
22.	Narlikar et al.	1975	Ap & SS, 35, 321	WH		COS	WH excites synchrotron emission, inverse Compton scattering
23.	Piran et al.	1975	Nature, 256, 112	BH		DISK	Inv Comp scat deep in ergosphere of fast rotating, accreting BH
24.	Fabian et al.	1976	Ap & SS, 42, 77	NS		DISK	NS crustquake shocks NS surface
25.	Chanmugam	1976	Ap & SS, 42, 83	WD		DISK	Magnetic WD suffers MHD instabilities, flares
26.	Mullan	1976	ApJ, 208, 199	WD		DISK	Thermal radiation from flare near magnetic WD
27.	Woosley et al.	1976	Nature, 263, 101	NS		DISK	Carbon detonation from accreted matter onto NS
28.	Lamb et al.	1977	ApJ, 217, 197	NS		DISK	Mag grating of accret disk around NS causes sudden accretion
29.	Piran et al.	1977	ApJ, 214, 268	BH		DISK	Instability in accretion onto rapidly rotating BH
30.	Dasgupta	1979	Ap & SS, 63, 517	DG		SOL	Charged intergal rel dust grain enters sol sys, breaks up
31.	Tsygan	1980	A&A, 87, 224	WD		DISK	WD surface nuclear burst causes chromospheric flares
32.	Tsygan	1980	A&A, 87, 224	NS		DISK	NS surface nuclear burst causes chromospheric flares
33.	Ramaty et al.	1981	Ap & SS, 75, 193	NS		DISK	NS vibrations heat atm to pair produce, annihilate, synch cool
34.	Newman et al.	1980	ApJ, 242, 319	NS	AST	DISK	Asteroid from interstellar medium hits NS
35.	Ramaty et al.	1980	Nature, 287, 122	NS		HALO	NS core quake caused by phase transition, vibrations
36.	Howard et al.	1981	ApJ, 249, 302	NS	AST	DISK	Asteroid hits NS, B-field confines mass, creates high temp
37.	Mitrofanov et al.	1981	Ap & SS, 77, 469	NS		DISK	Helium flash cooled by MHD waves in NS outer layers
38.	Colgate et al.	1981	ApJ, 248, 771	NS	AST	DISK	Asteroid hits NS, tidally disrupts, heated, expelled along B lines
39.	van Buren	1981	ApJ, 249, 297	NS	AST	DISK	Asteroid enters NS B field, dragged to surface collision
40.	Kuznetsov	1982	CosRes, 20, 72	MG		SOL	Magnetic reconnection at heliopause

Nemiroff, 1993

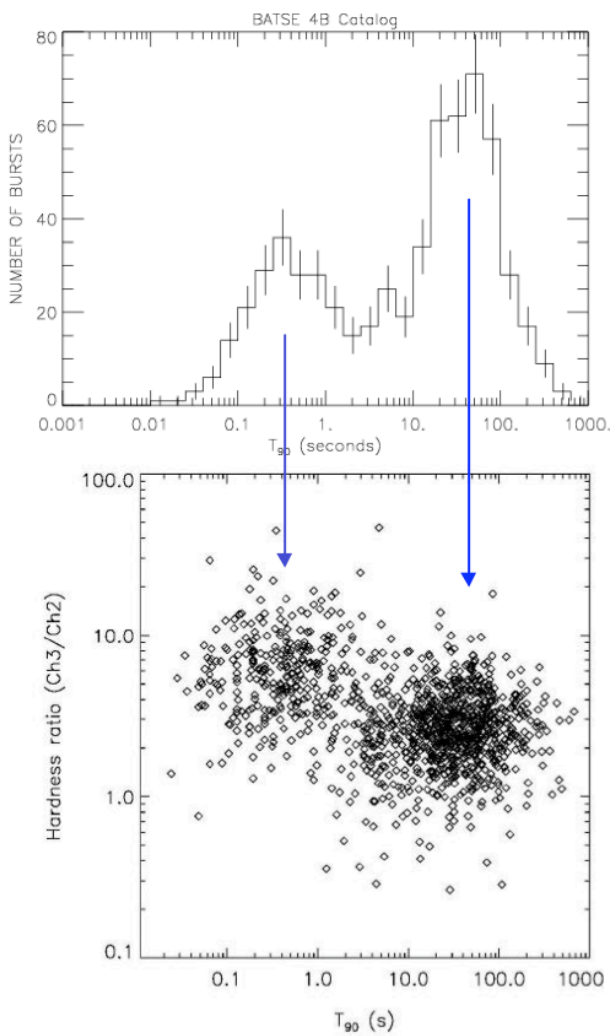
Stage 2: 1991-1996
(CRGO era)

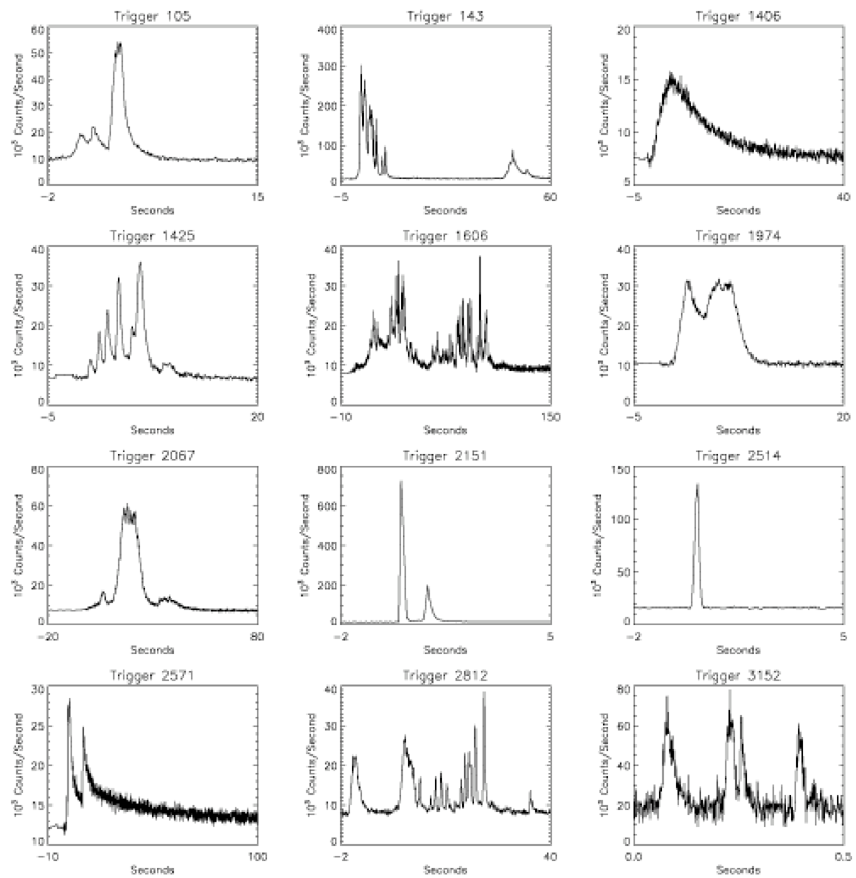


Two major advances:

1. **Two types:**
   Long/soft vs. short/hard
2. **Isotropic distribution**

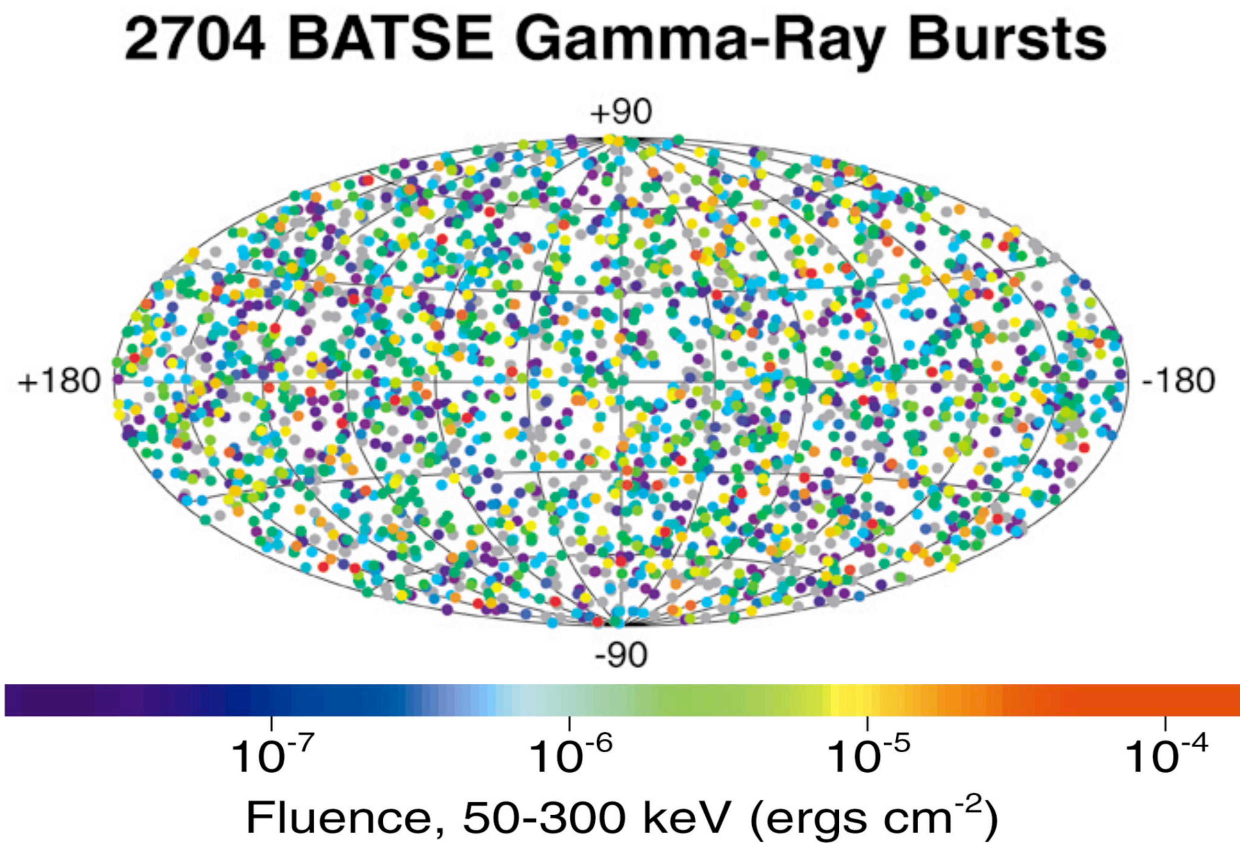
Short/Hard vs. Long/Soft





BATSE results (Kouveliotou et al. 1993)

Isotropic Distribution



Distance and Energetics

Galactic:

$$L_\gamma(\text{iso}) = 4\pi d^2 F_\gamma = 1.2\times 10^{42}\,\text{erg/s}\left(\frac{d}{30\text{kpc}}\right)^2\left(\frac{F_\gamma}{10^{-5}\,\text{erg/s/cm}^2}\right)$$

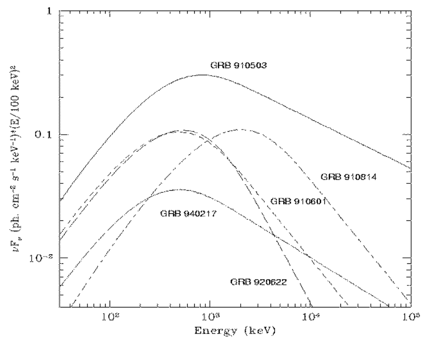
Cosmological:

$$L_\gamma(\text{iso}) = 4\pi d^2 F_\gamma = 1.2\times 10^{51}\,\text{erg/s}\left(\frac{d}{1\text{Gpc}}\right)^2\left(\frac{F_\gamma}{10^{-5}\,\text{erg/s/cm}^2}\right)$$

For comparison:

$$L_\otimes \sim 10^{33}\,\text{erg/s},\ \ L_{gal} \sim 10^{44}\,\text{erg/s},\quad L_{\text{AGN,M}} \sim 10^{48}\,\text{erg/s}$$

?

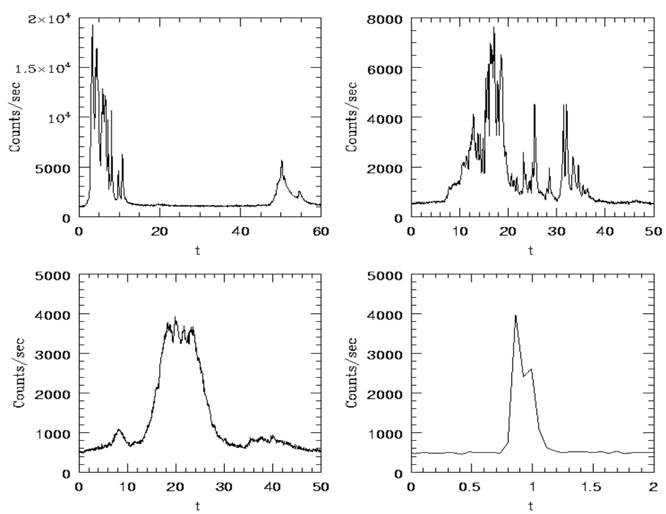

GRB 910503
GRB 910814
GRB 910601
GRB 940217
GRB 920622
Energy (keV)

?

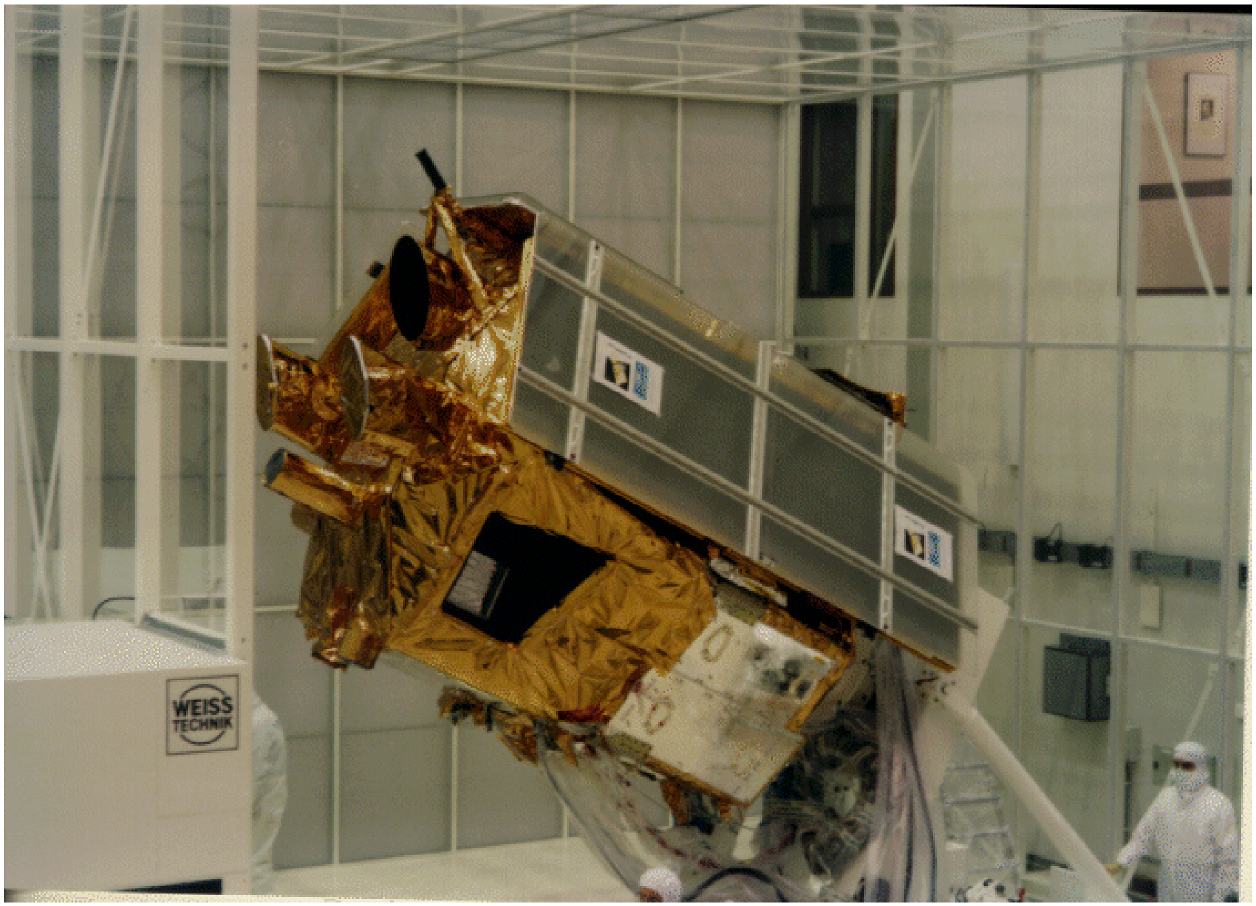
GRB

time

?


Counts/sec
t

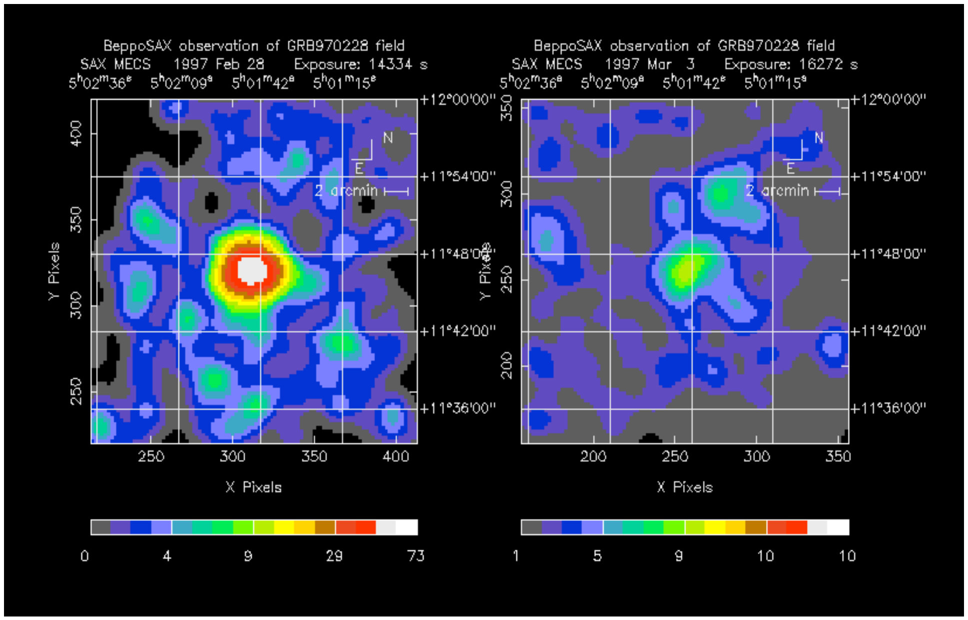
Stage 3: 1997-2003
(BeppoSAX-HETE era)



Three major advances:

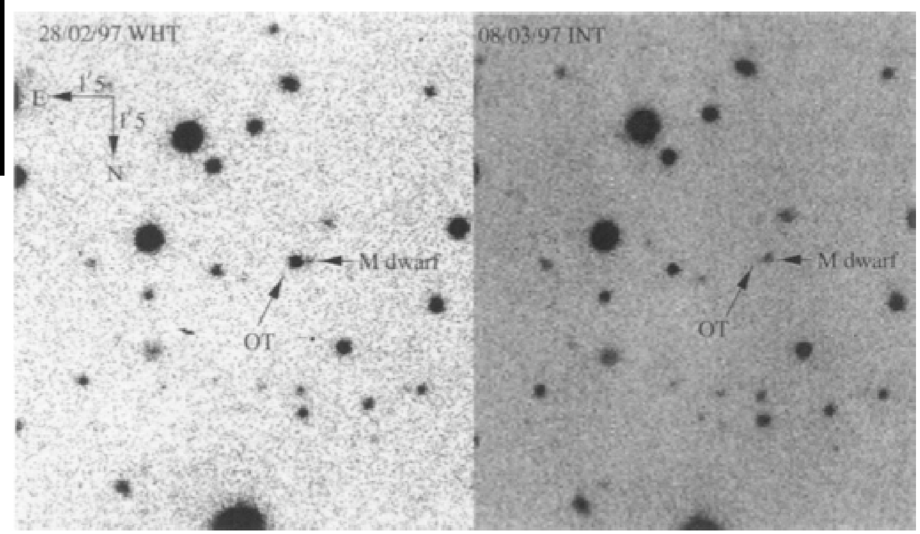
1. **Afterglow of long GRBs (as predicted by the fireball model) - host galaxy, redshift …**
2. **SN association with some long GRBs - massive star origin**
3. **Collimation of jets**

Discovery of afterglow of long GRBs



GRB 970228

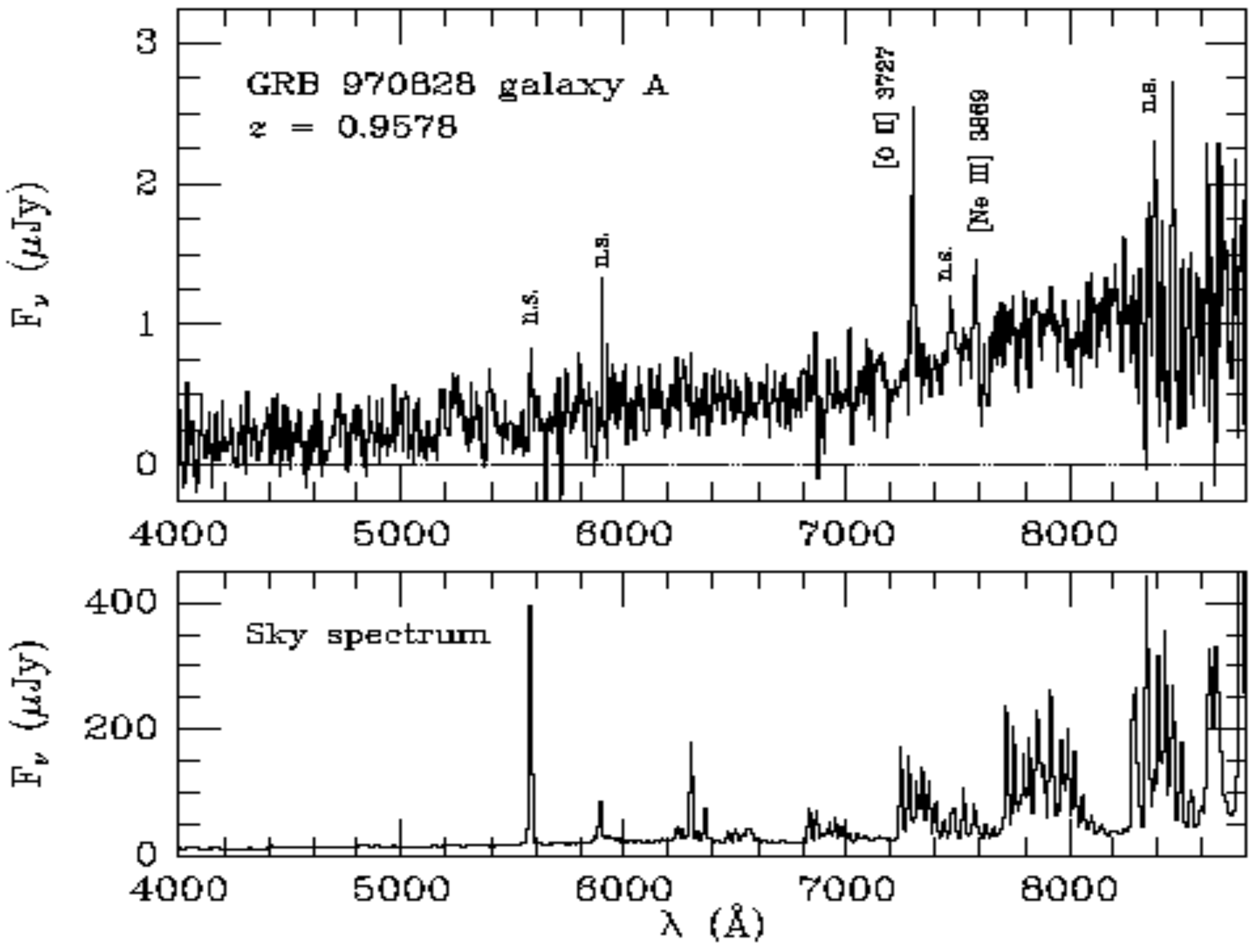
X-ray afterglow: Costa et al. 1997



Optical afterglow: van Paradijs 1997

NATURE | VOL 386 | 17 APRIL 1997

Measuring redshift of long GRBs



GRBs are at cosmological distances, and GRBs are the most luminous explosions in the universe.

Metzger et al. 2007

Distance and Energetics

Galactic:

$$L_\gamma(\mathrm{iso}) = 4\pi d^2 F_\gamma = 1.2\times10^{42}\,\mathrm{erg/s}\left(\frac{d}{30\mathrm{kpc}}\right)^2\left(\frac{F_\gamma}{10^{-5}\,\mathrm{erg/s/cm^2}}\right)$$

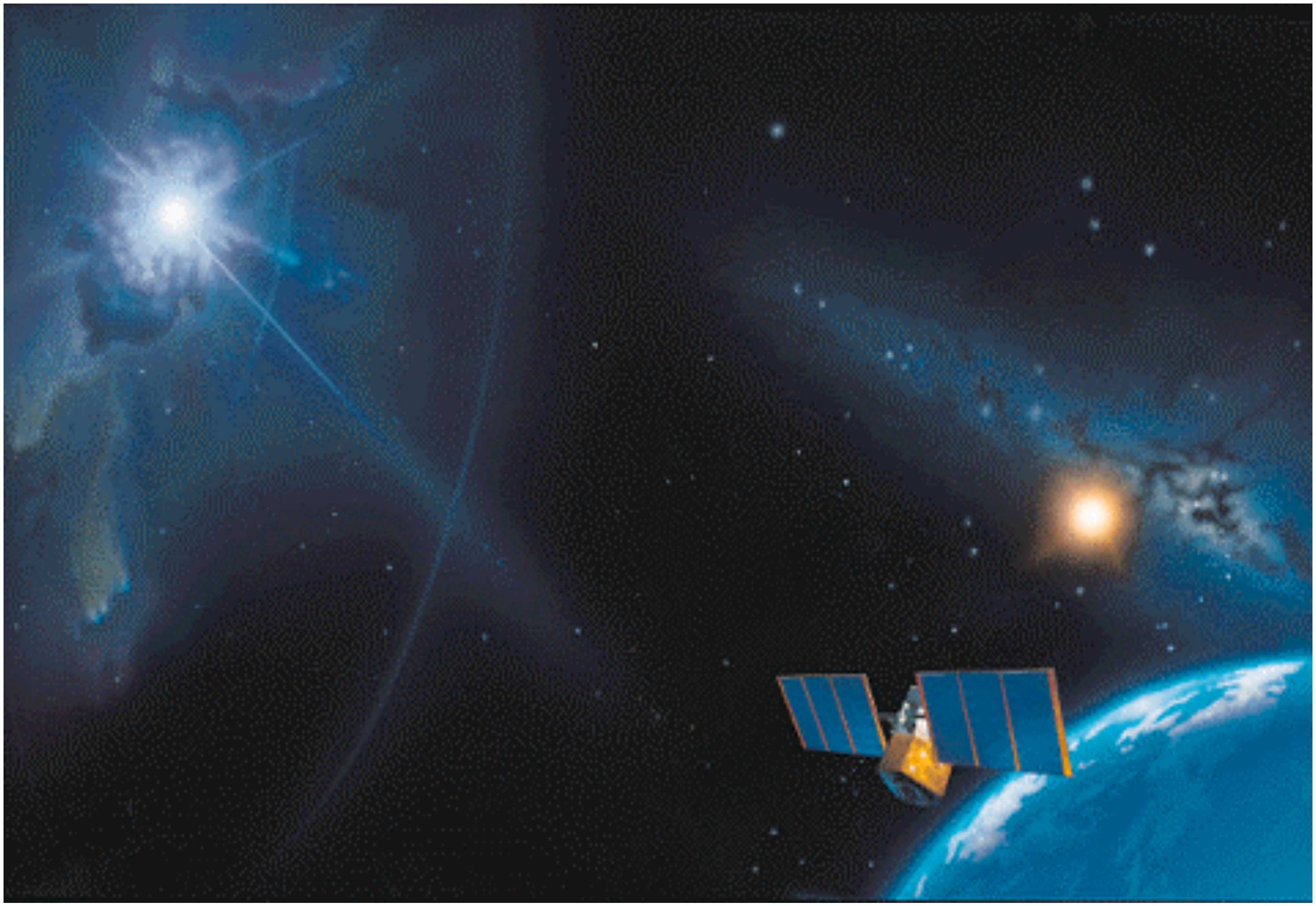
Cosmological:

$$L_\gamma(\mathrm{iso}) = 4\pi d^2 F_\gamma = 1.2\times10^{51}\,\mathrm{erg/s}\left(\frac{d}{1\mathrm{Gpc}}\right)^2\left(\frac{F_\gamma}{10^{-5}\,\mathrm{erg/s/cm^2}}\right)$$

For comparison:

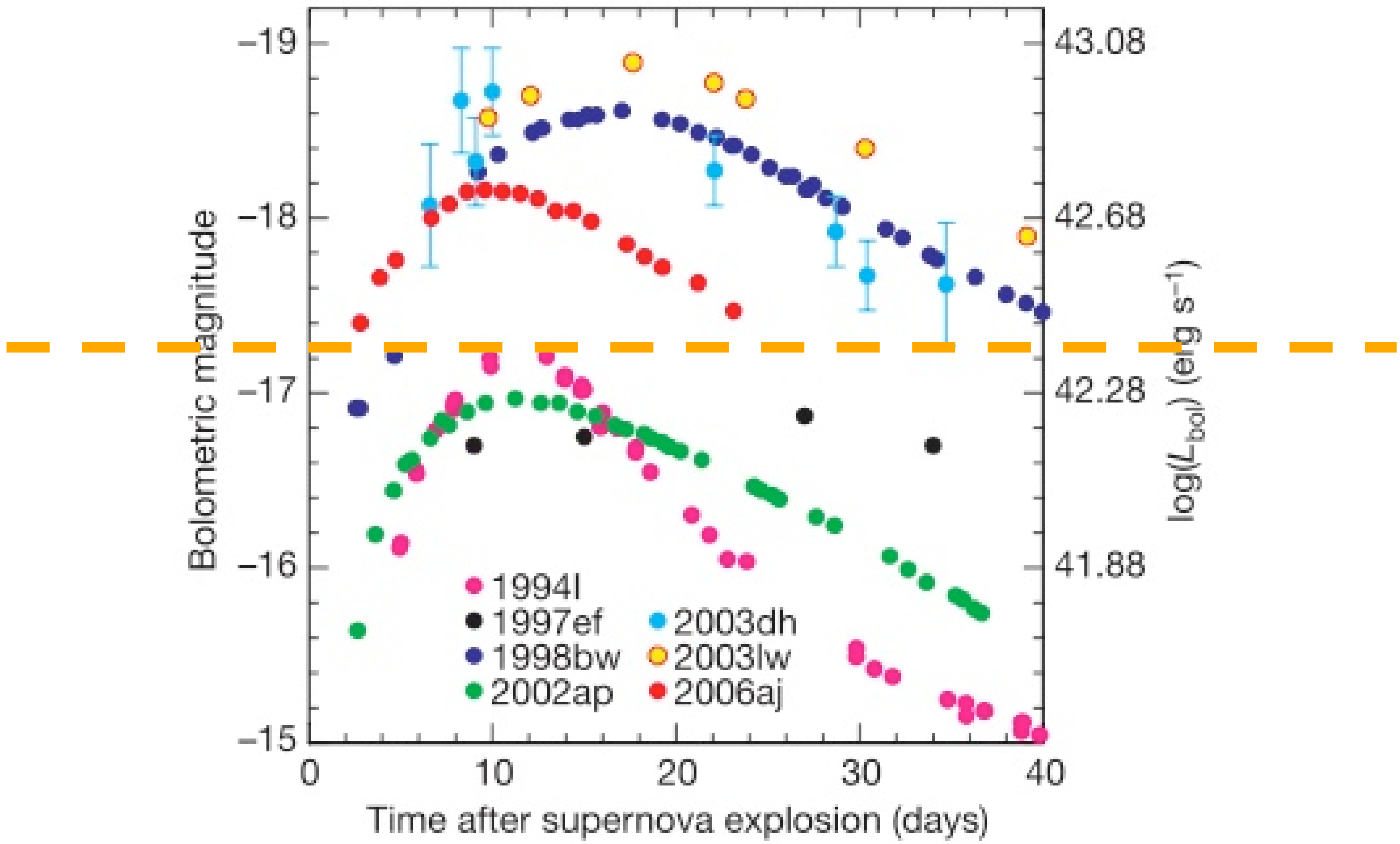
$$L_\otimes \sim 10^{33}\,\mathrm{erg/s},\ \ L_{gal} \sim 10^{44}\,\mathrm{erg/s},\ \ \ L_{\mathrm{AGN,M}} \sim 10^{48}\,\mathrm{erg/s}$$

Gamma-ray bursts: the most violent explosions after Big Bang!

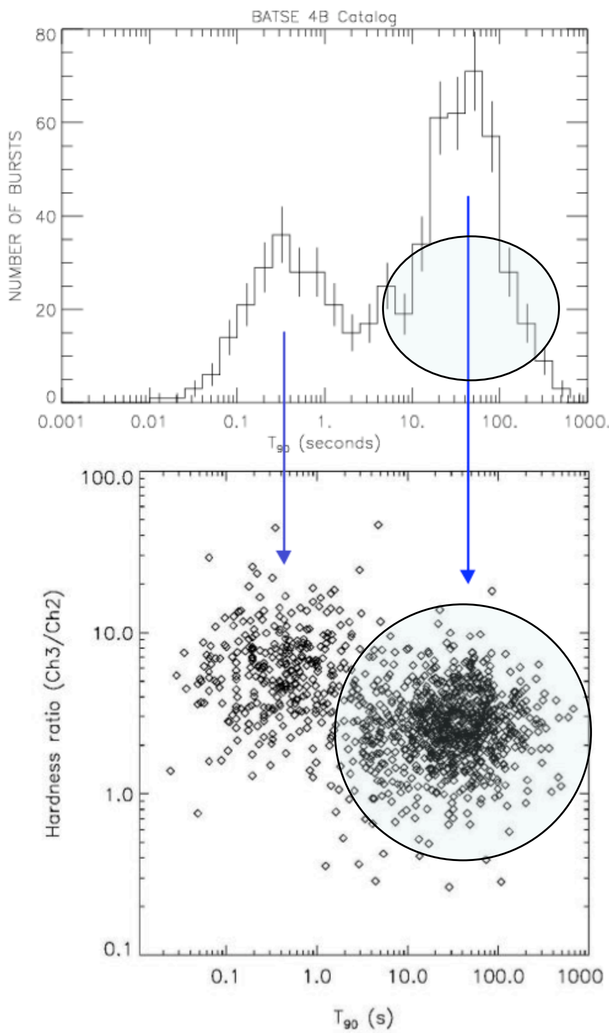


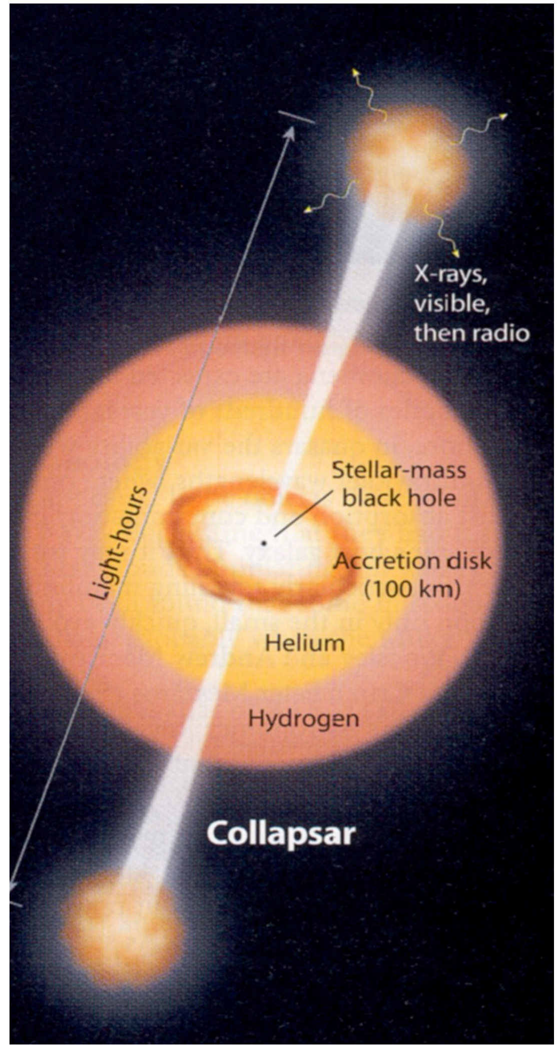
GRB/SN associations - SN properties

(Pian et al. 2007)



Collapsars: model for long GRBs

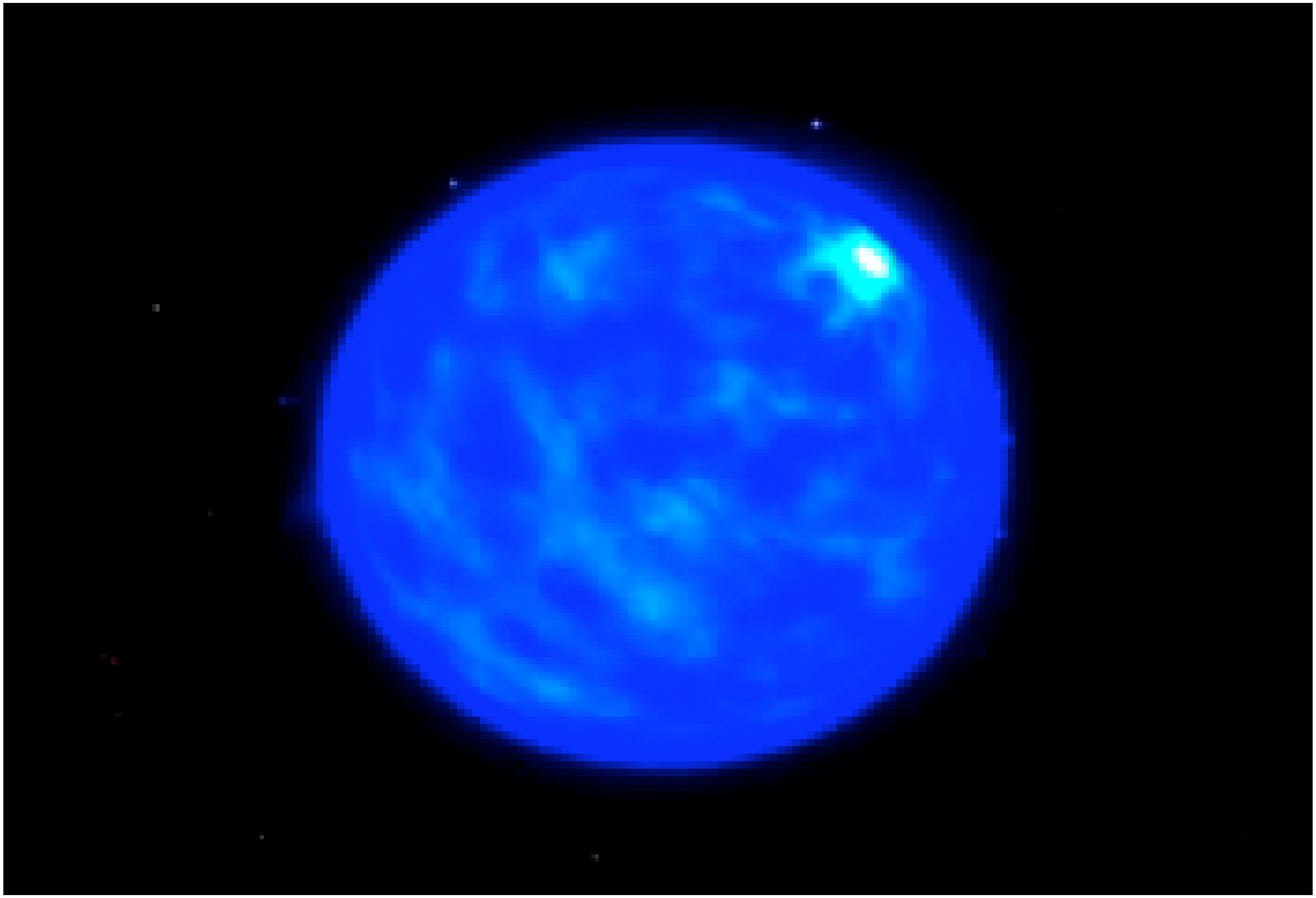




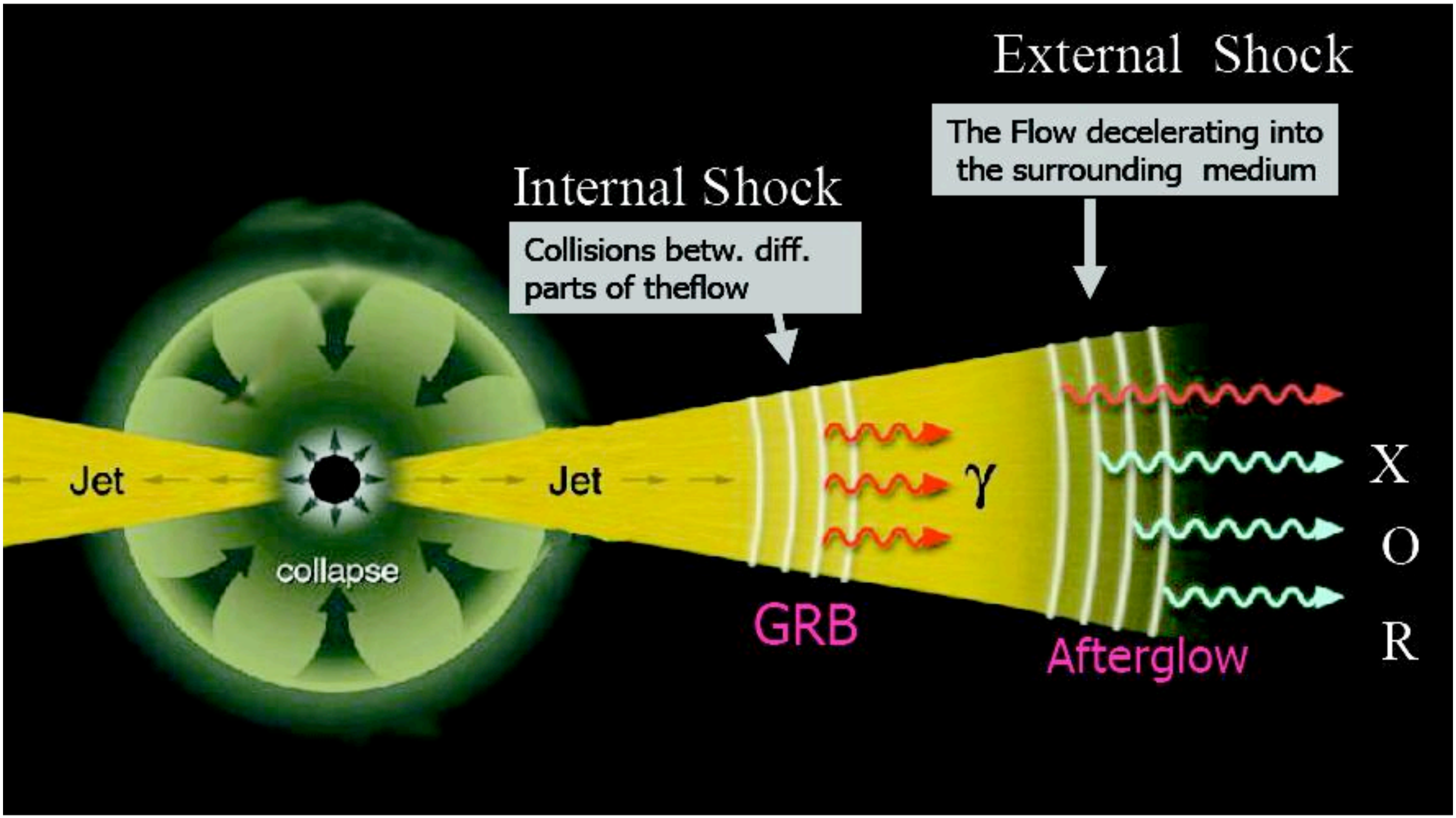
Woosley 93

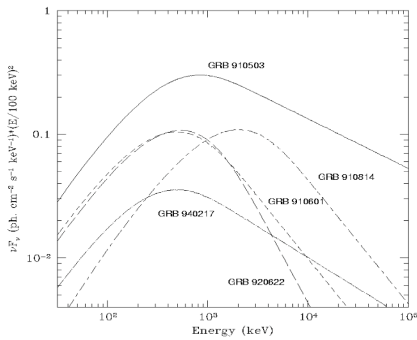
MacFadyen & Woosley 99

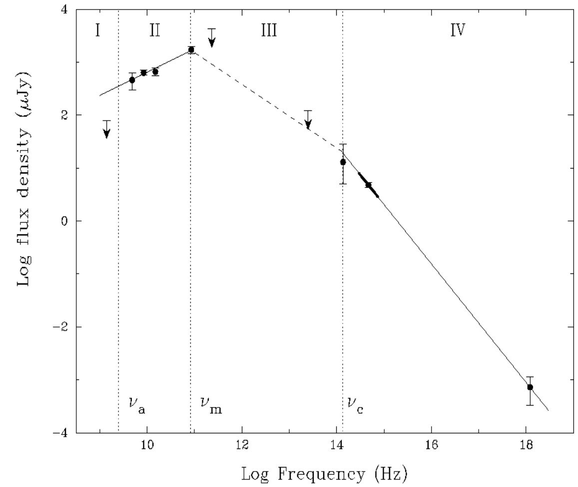
GRB from a collapsing star



“Generic” Fireball Shock Model







GRB

afterglow

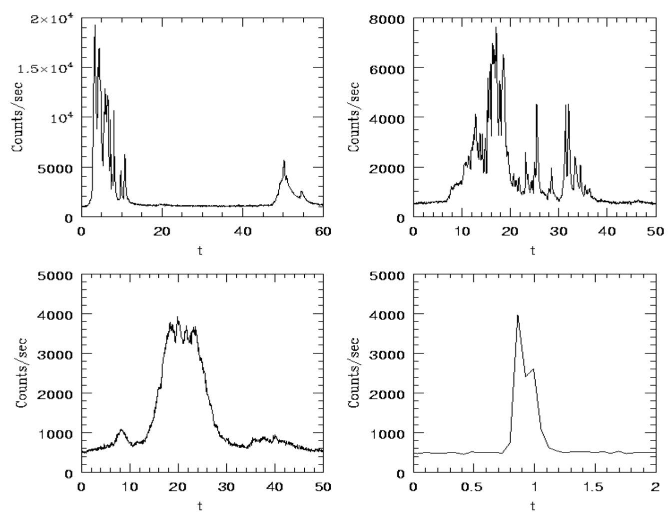
time

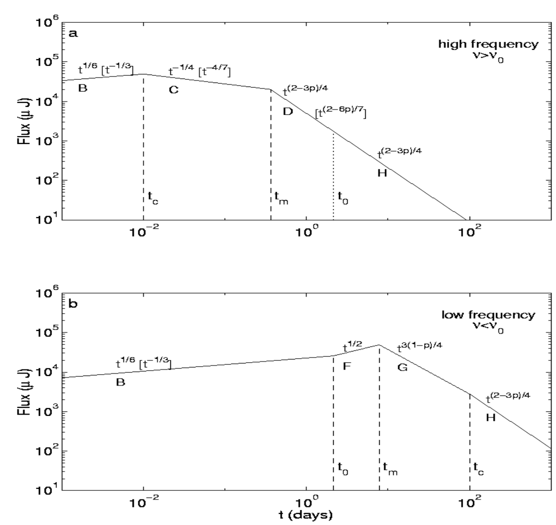
hours

1 day

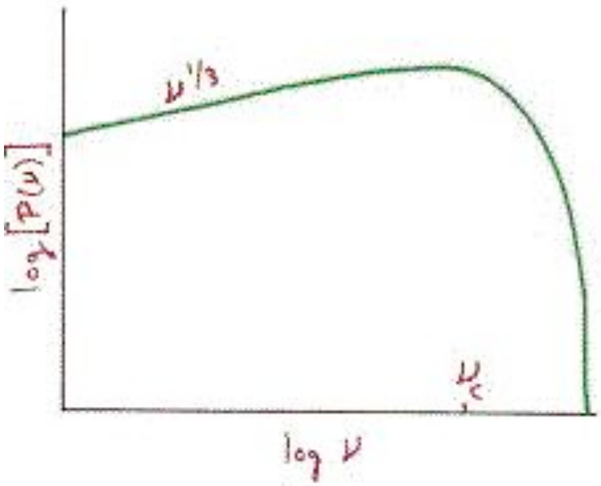
1 mon

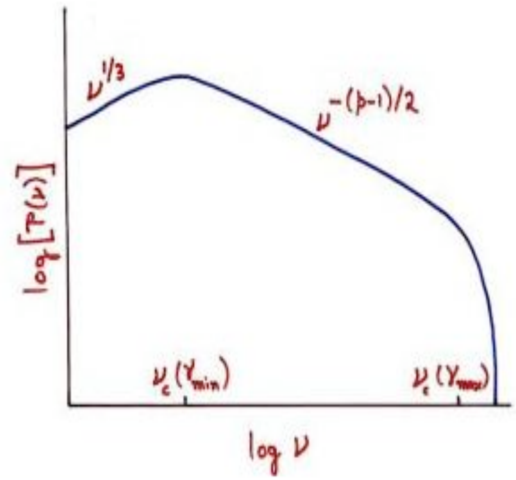
1 yr

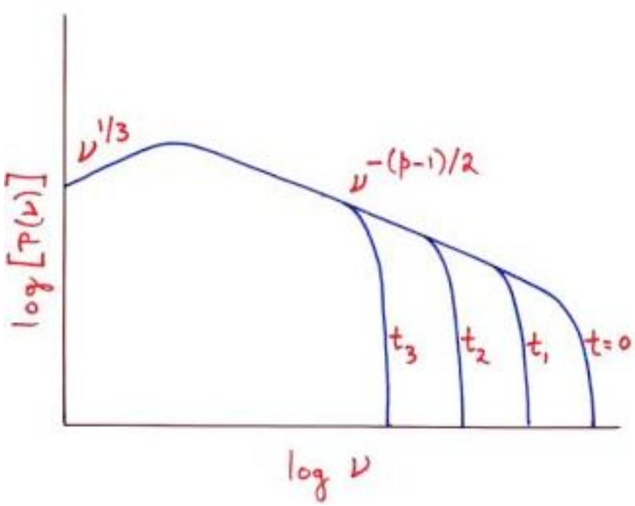




Synchrotron radiation (1)



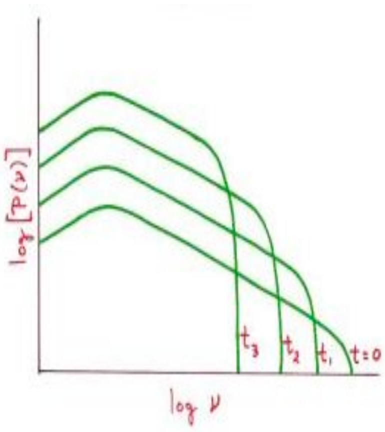


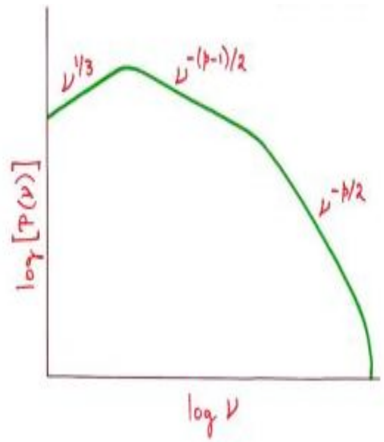


- Single electron emission;
- Emission from power-law electrons;
- Cooling spectrum;

Meszaros & Rees 1997; Sari, Piran & Narayan 1998

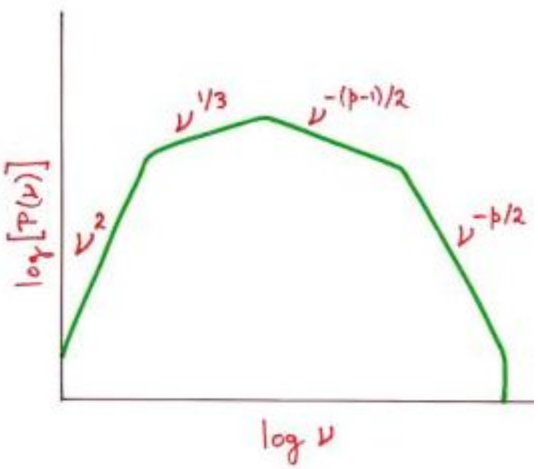
Synchrotron radiation (2)

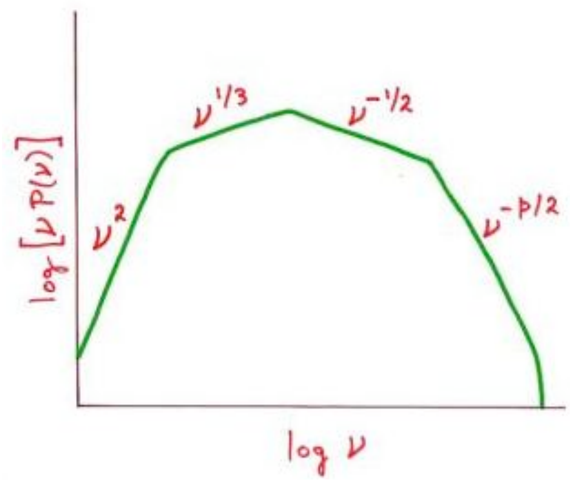




- Continuous acceleration;
- Self-absorption

Slow cooling

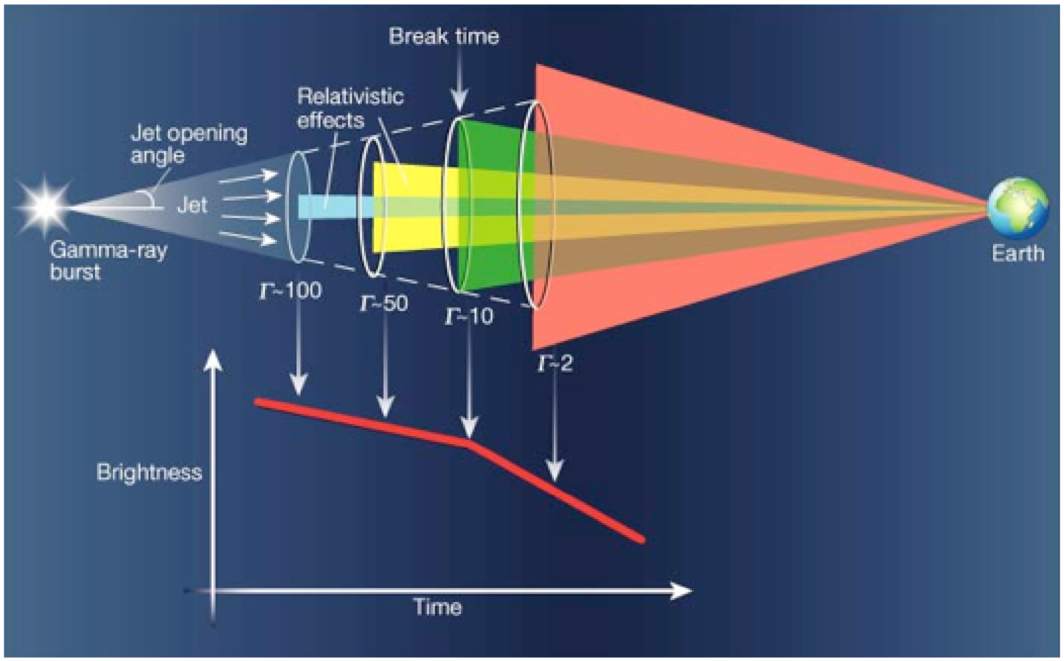


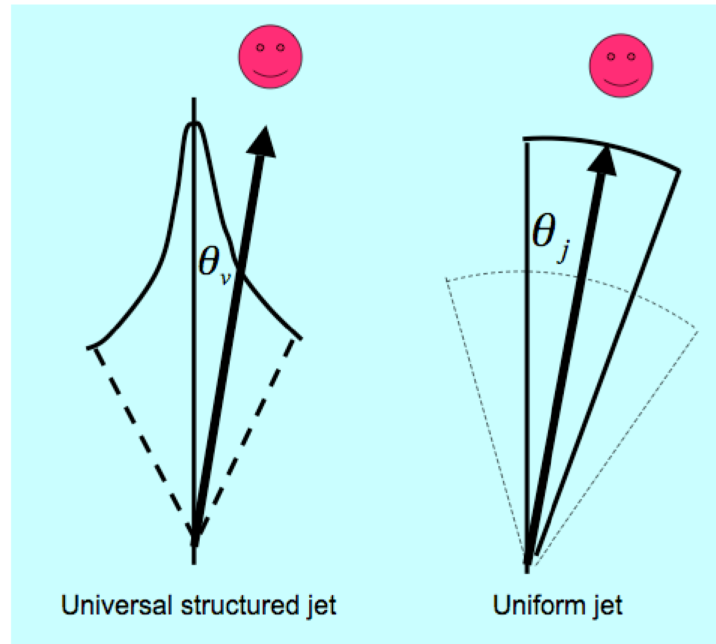


Fast cooling

Meszaros & Rees 1997; Sari, Piran & Narayan 1998

GRB collimation (Jet)

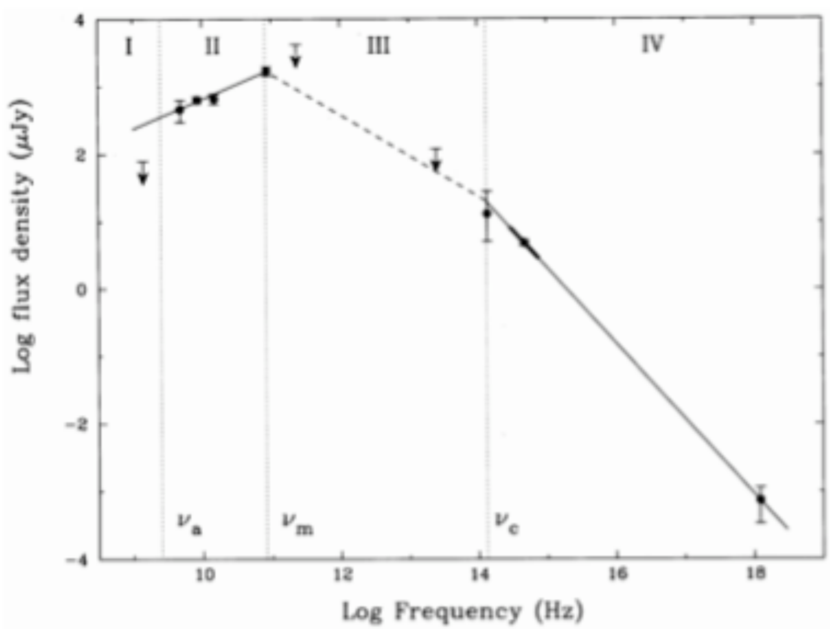




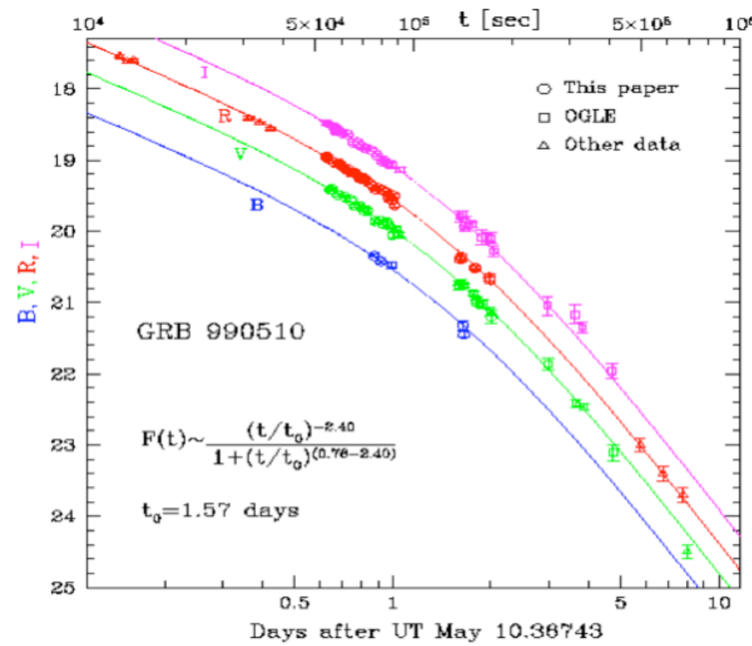
Rhoads 1997, 1999; Sari et al. 1999

Structured vs. uniform jets
Zhang & Meszaros 2002
Rossi, Lazzati & Rees 2002

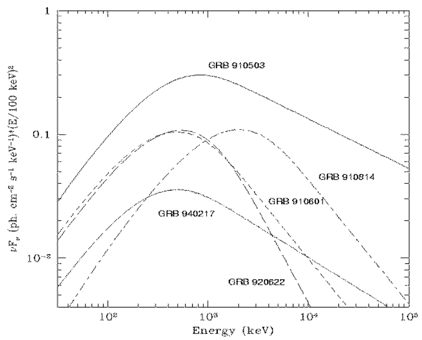
Confronting data with theory

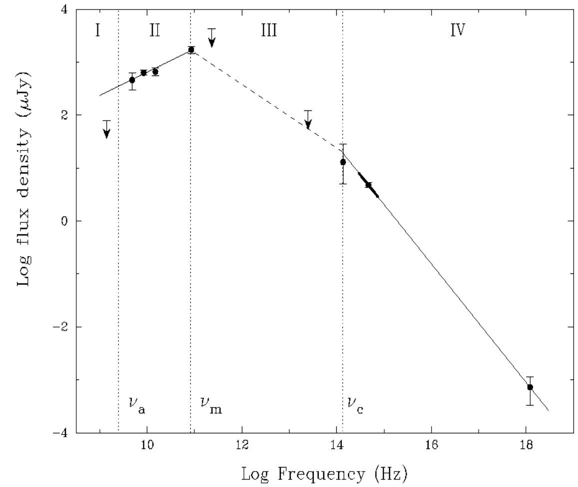


Wijers & Galama 99



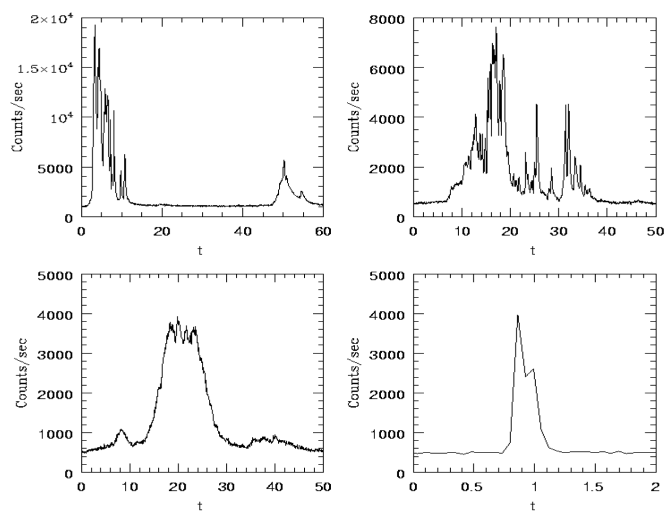
Stanek et al. 99

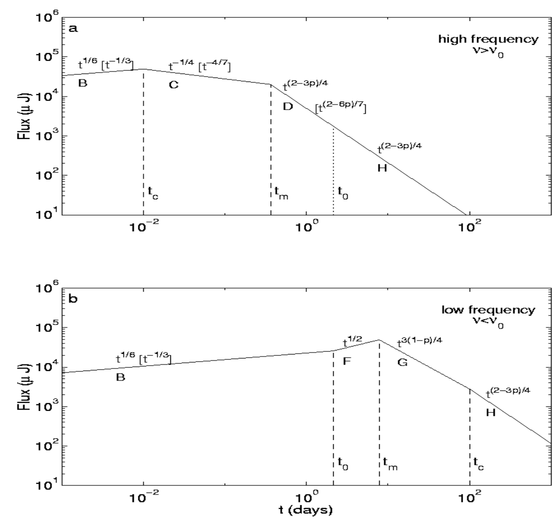




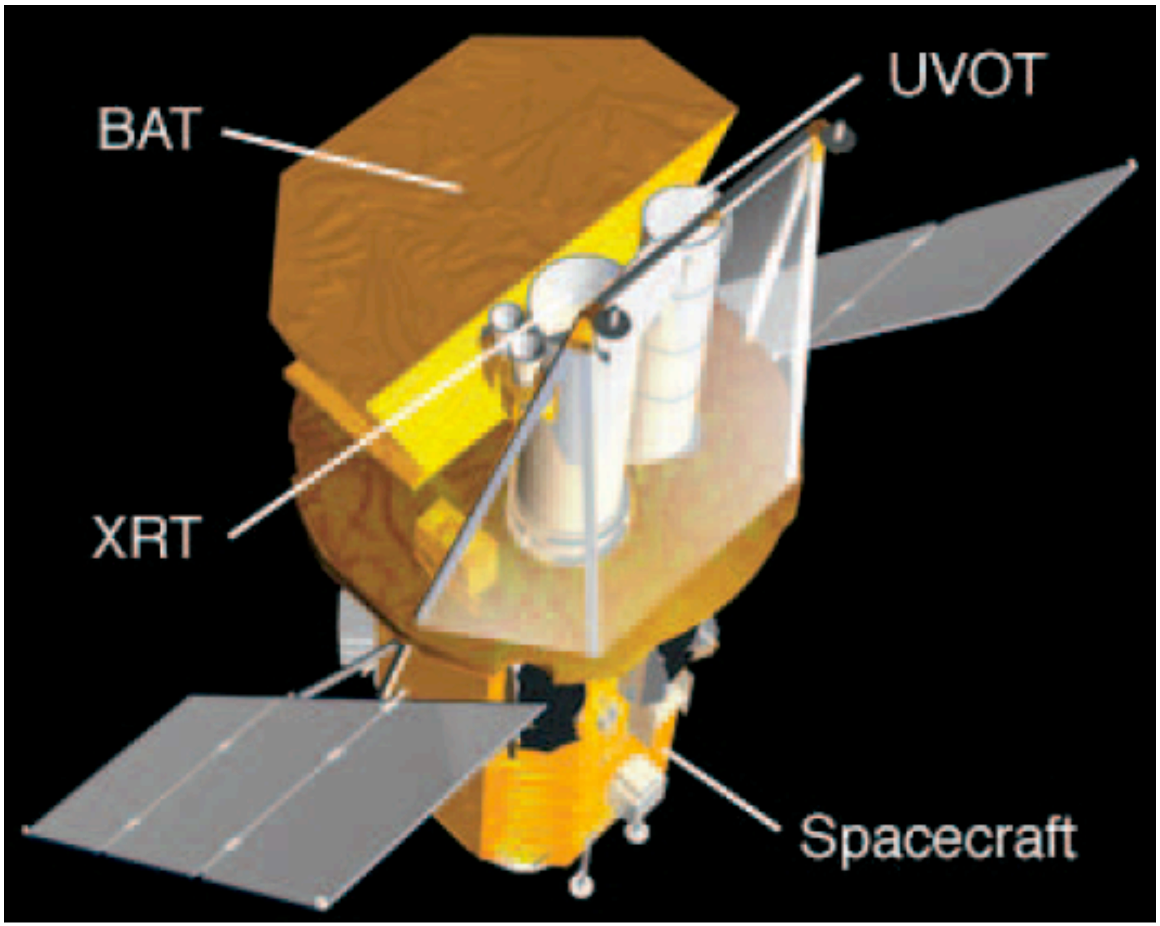
GRB **afterglow**

time **hours** **1 day** **1 mon** **1 yr**





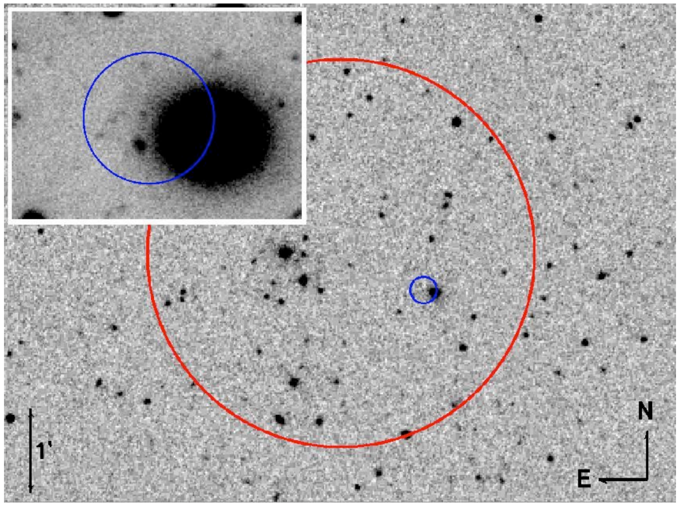
Stage 4: 2004-2008
(Swift era)



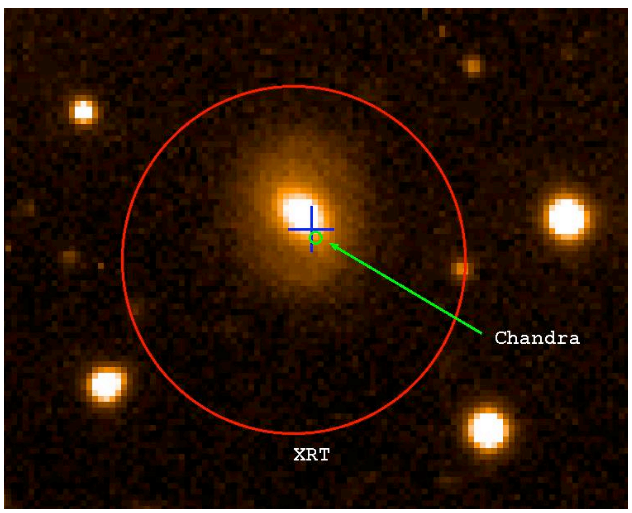
Three major advances:

1. **Short GRB afterglow**
2. **Canonical X-ray afterglow revealing mixed afterglow emission**
3. **Diversity of GRBs**

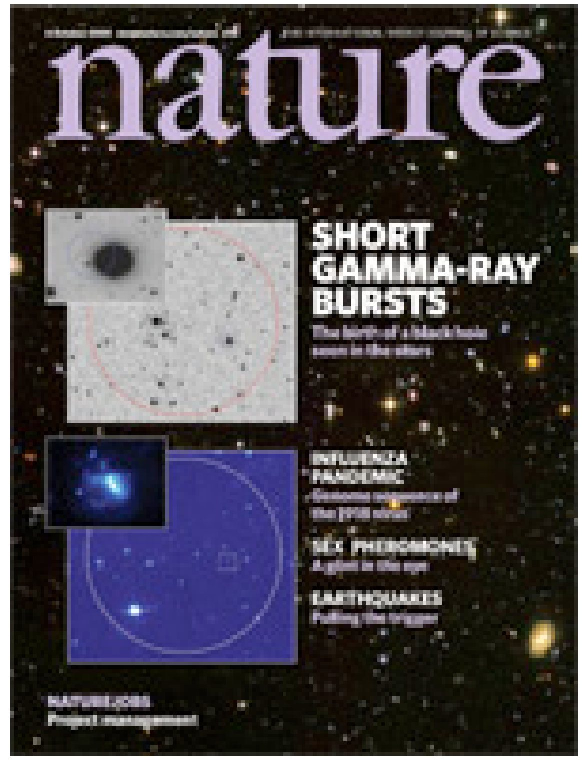
Swift & 2005 Revolution



GRB 050509B

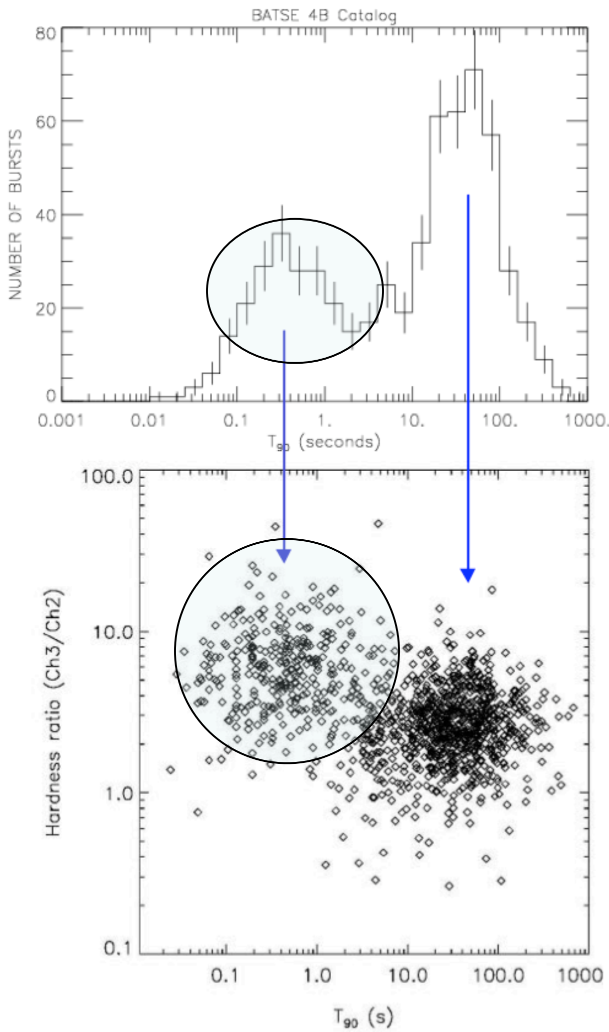


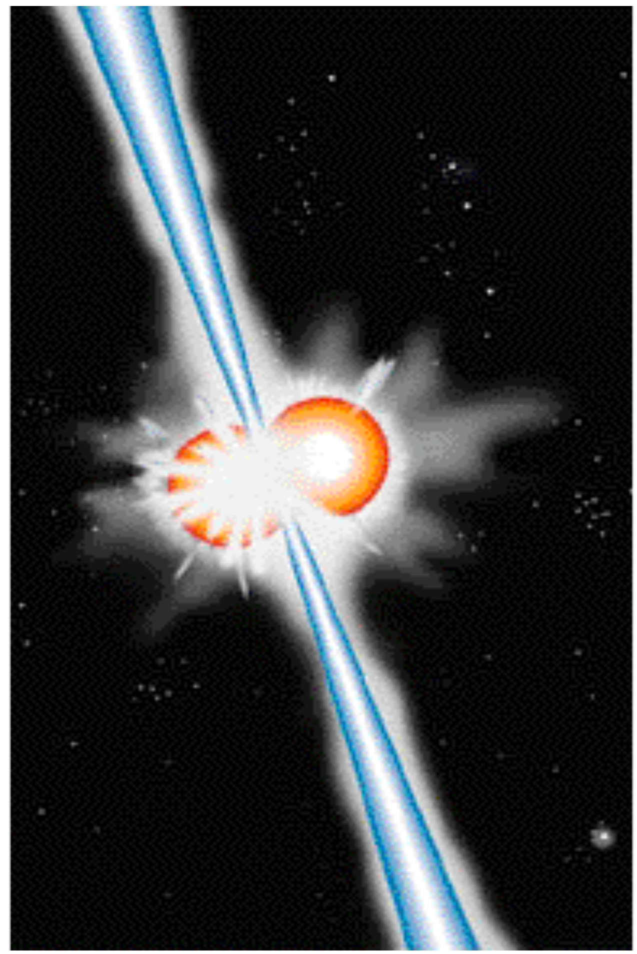
GRB 050724



Gehrels et al. 2005; Fox et al. 2005; Barthelmy et al. 2005; Berger et al. 2005

Compact star mergers: model for short GRBs

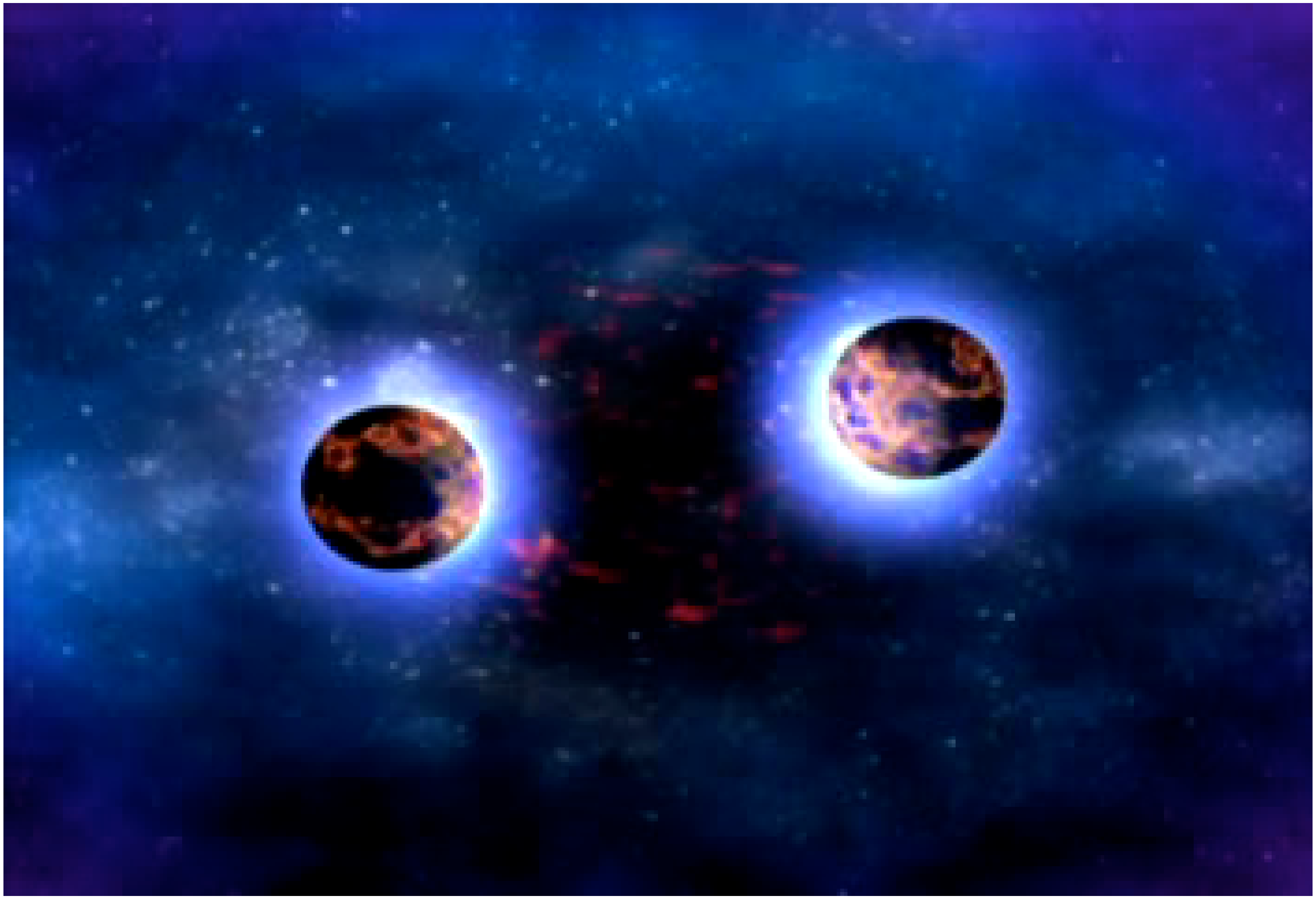




Paczynski 86

Eicher et al. 89

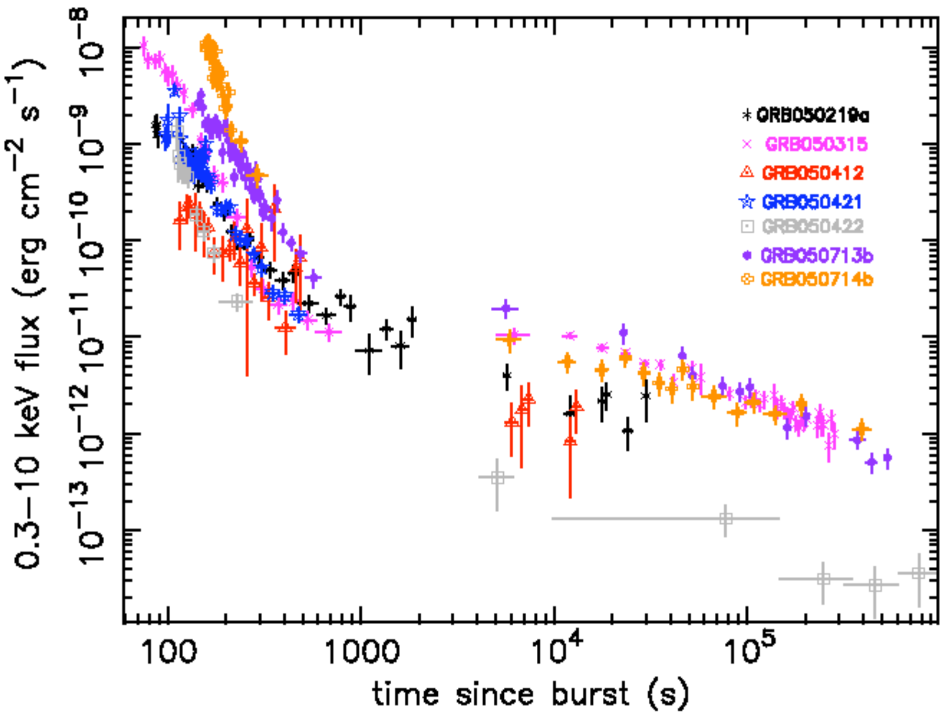
NS-NS merger

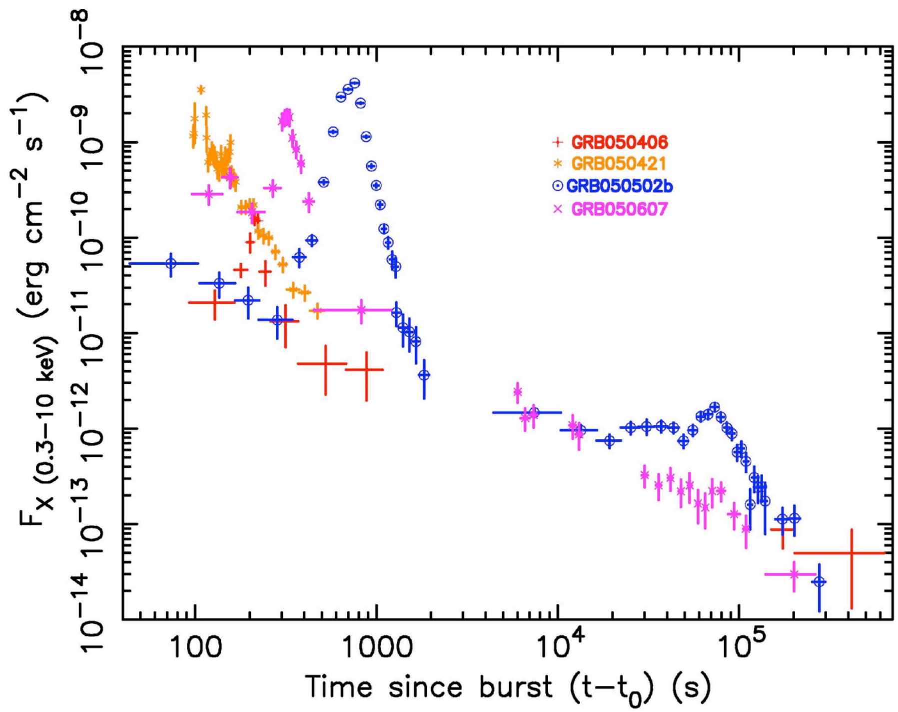


NS-BH merger

Typical XRT afterglow

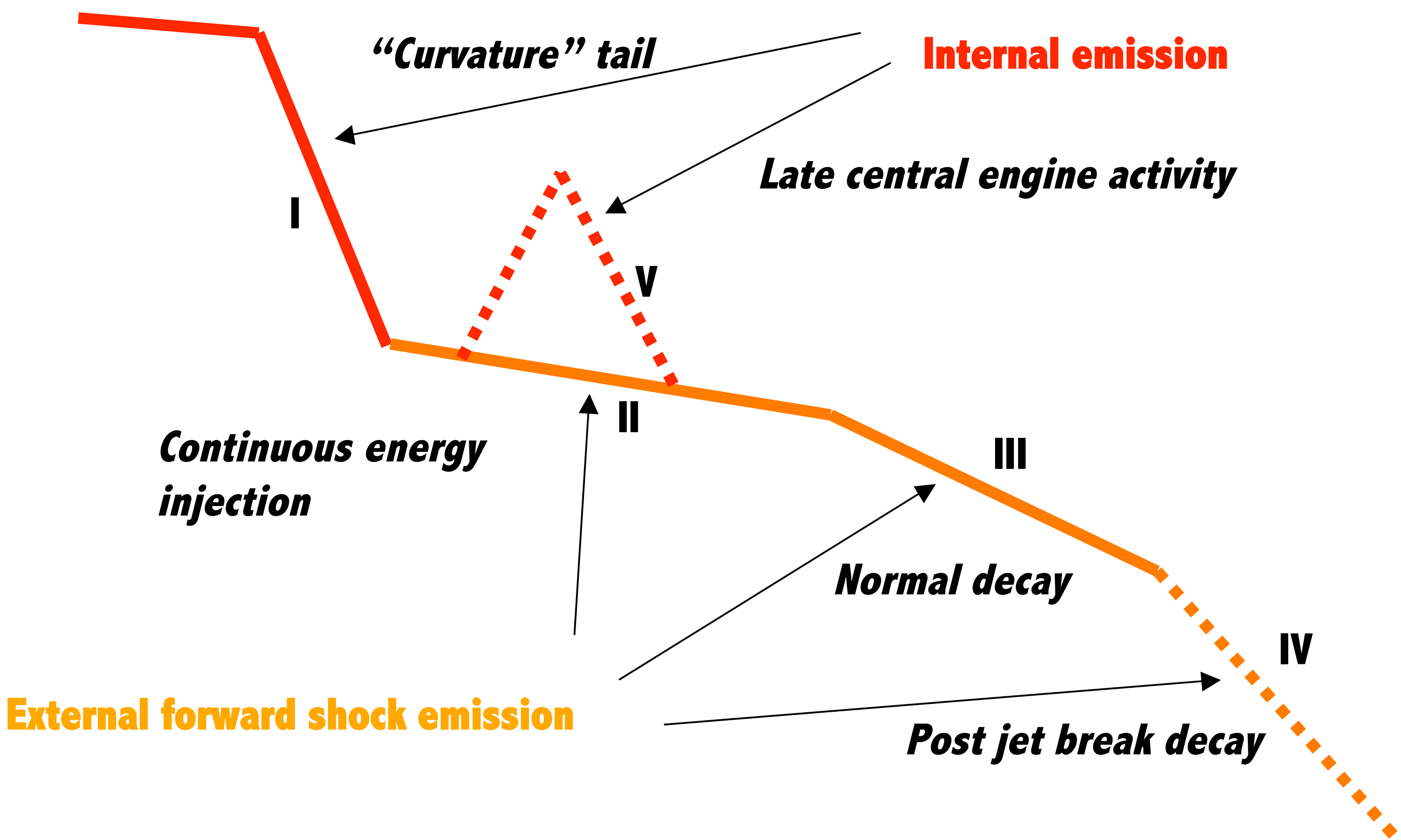
(Nousek et al. 2006, ApJ; O'Brien et al., 2006, ApJ)





Canonical lightcurves: Internal or external?

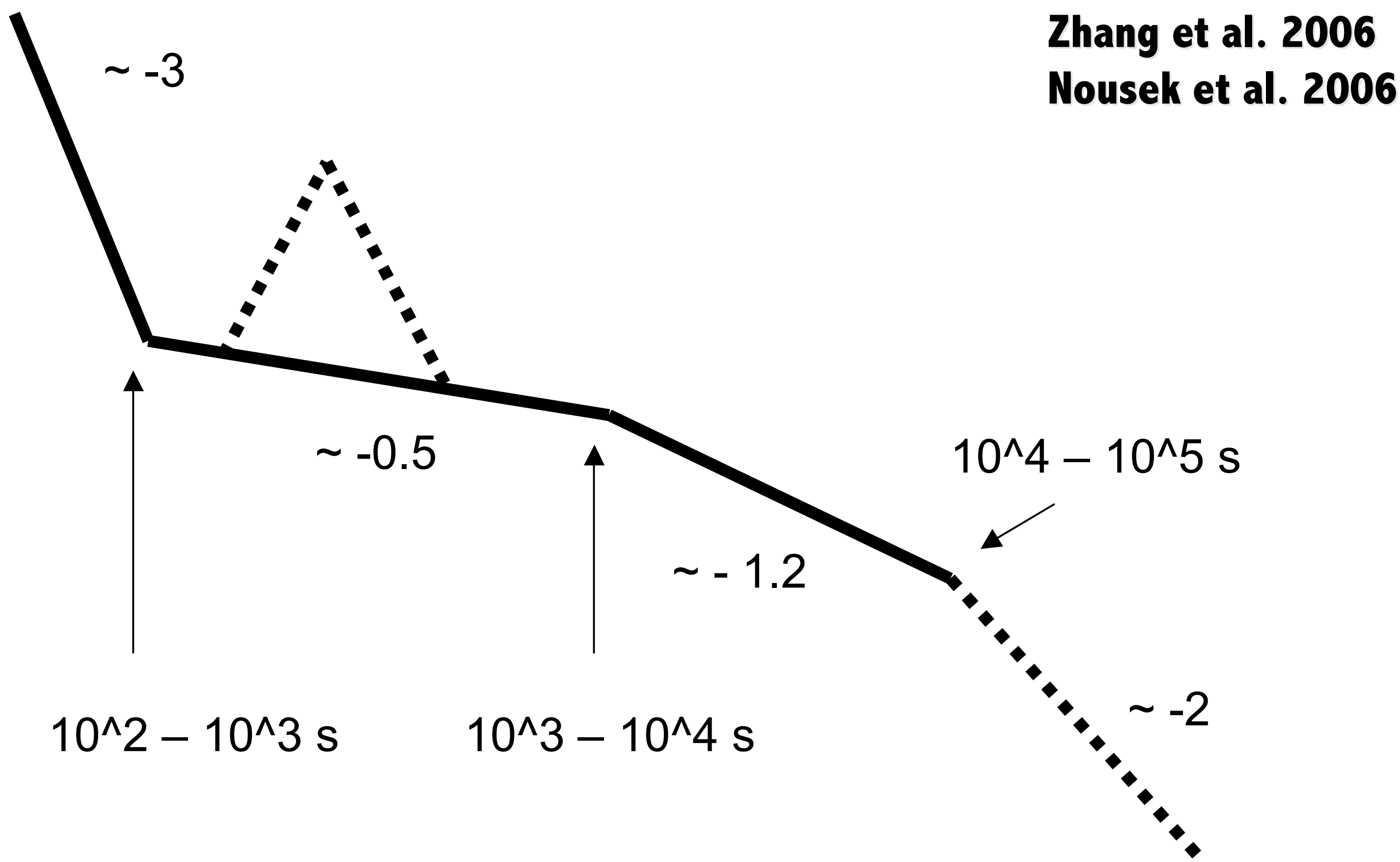
(Zhang et al. 2006; Nousek et al. 2006; Panaitescu et al. 2006)

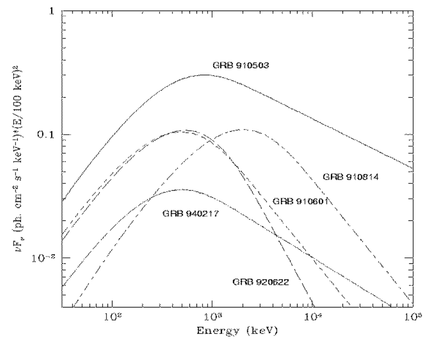


Swift revolution:

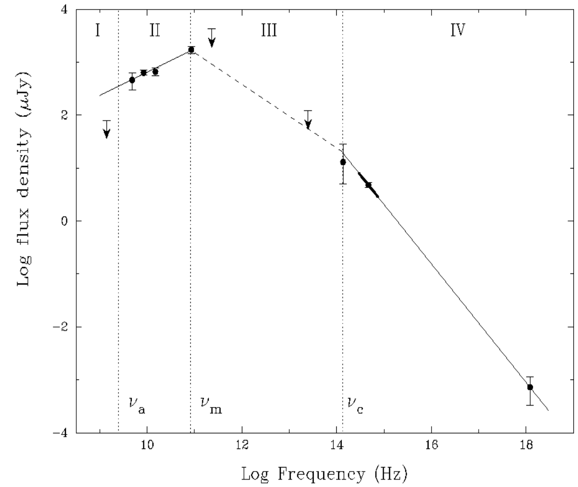
Prompt GRB emission: internal emission

Afterglow: superposition of external and internal emission





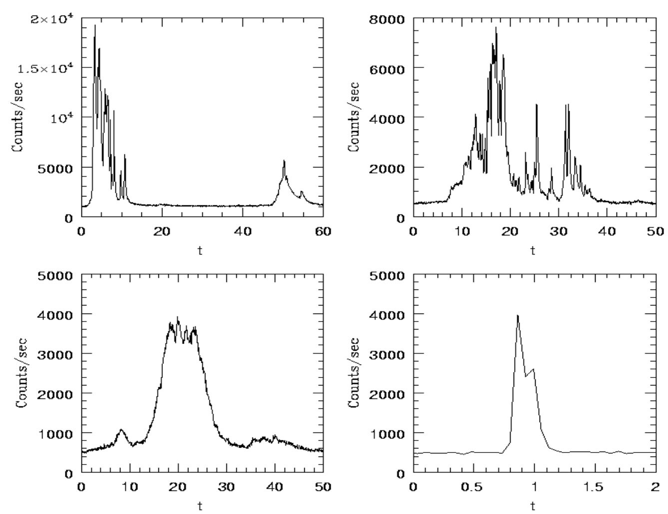
?

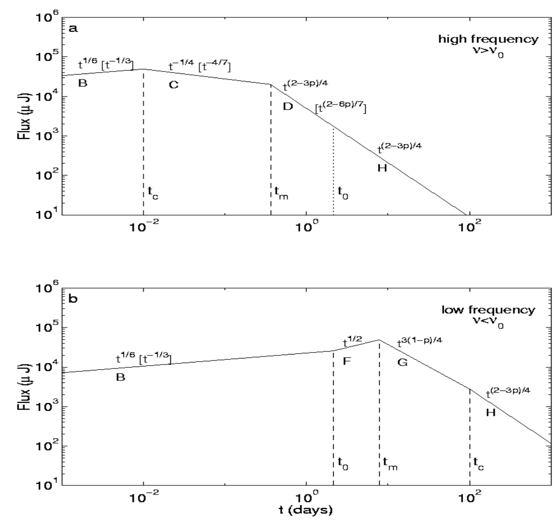


?

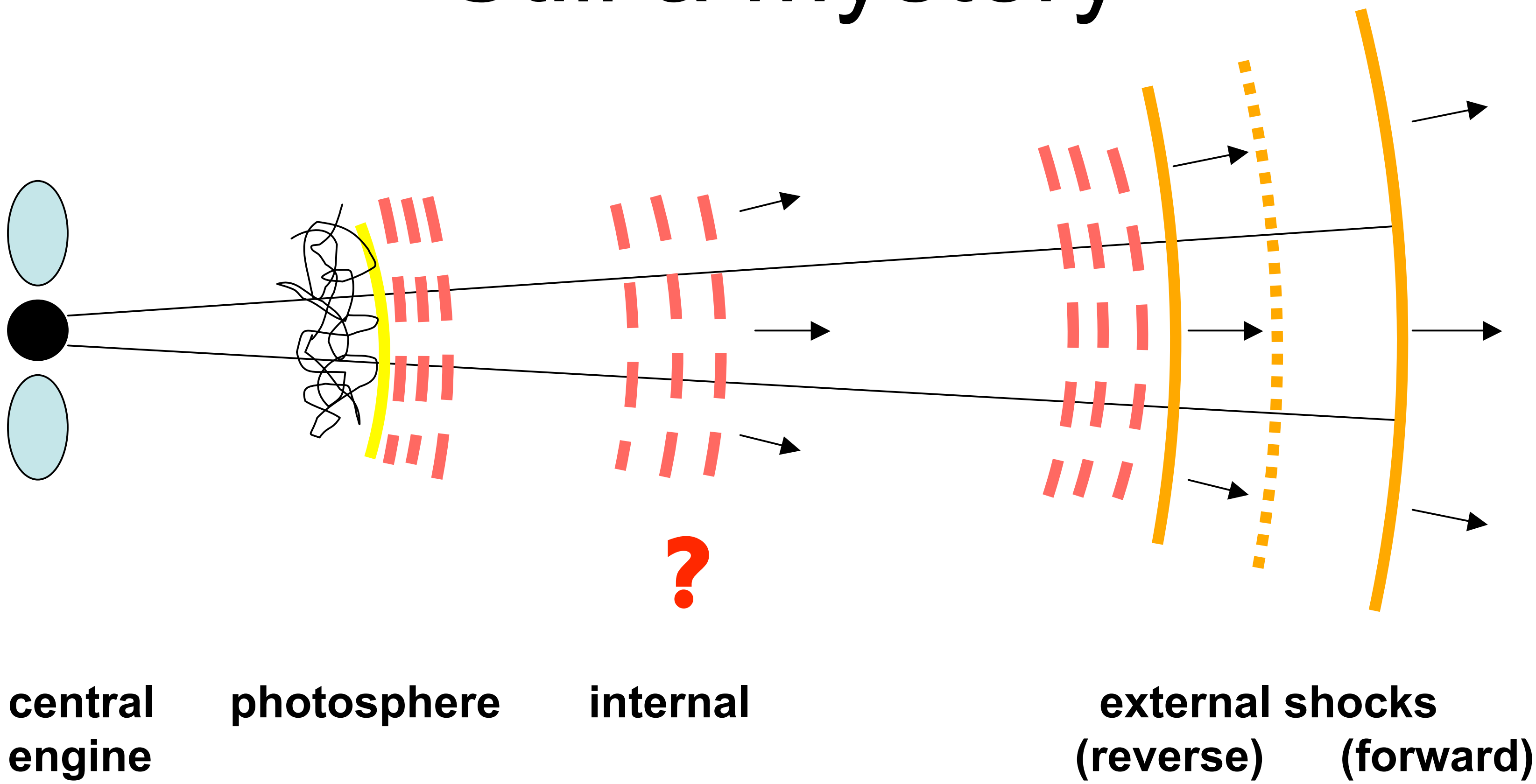
GRB **afterglow**

time ? **1 min** **1 day** **1 mon** **1 yr**





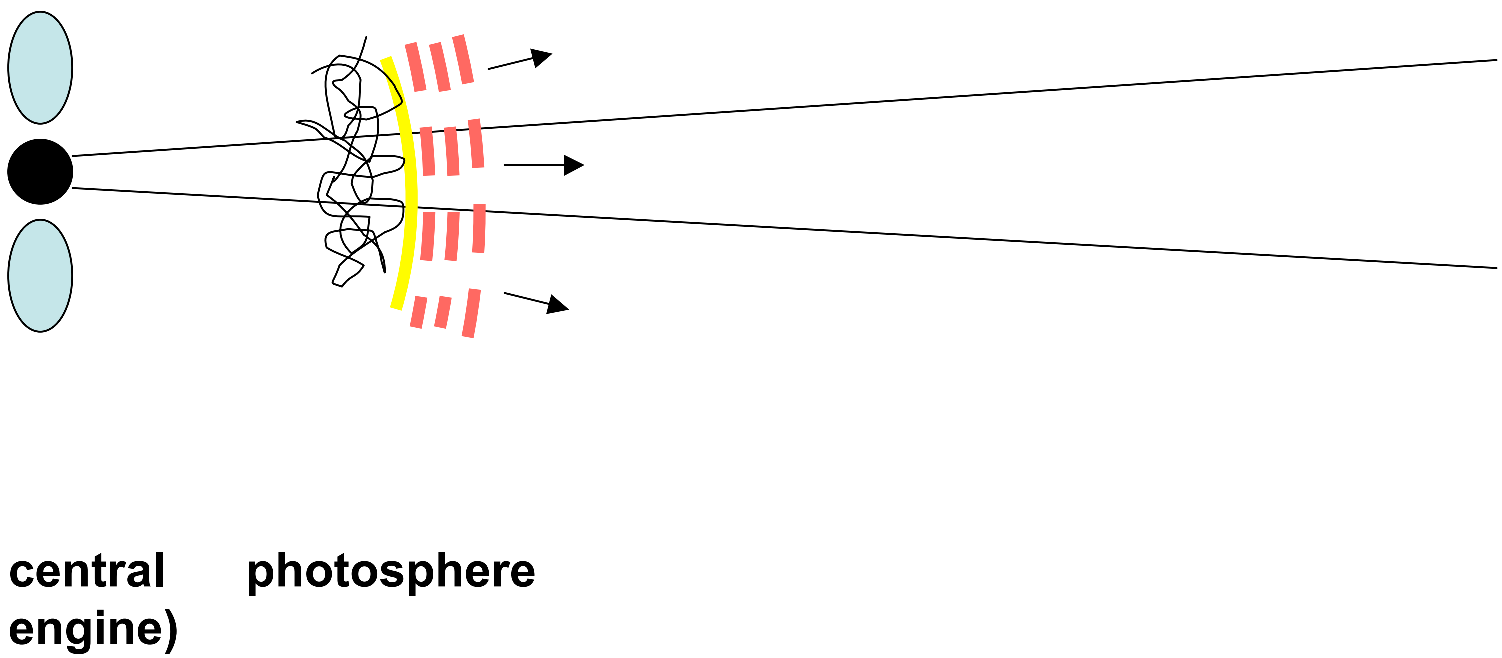
Prompt GRB Emission: Still a Mystery



What is the jet composition (baryonic vs. Poynting flux)?
Where is (are) the dissipation radius (radii)?
How is the radiation generated (synchrotron, Compton scattering, thermal)?

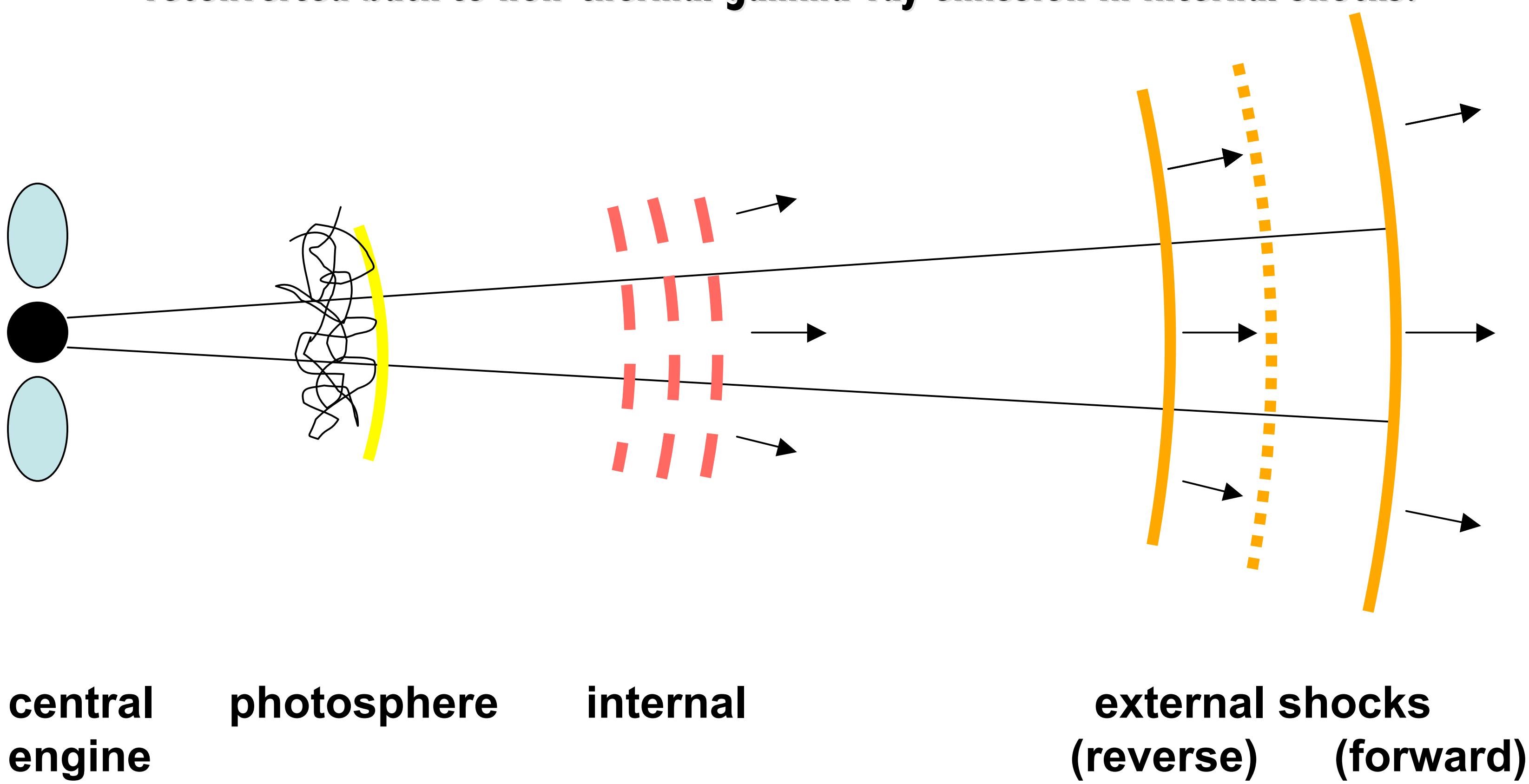
Historical Remark (1)

- Paczynski (86) & Goodman (86): a fireball of photons, electron-positron pairs expands freely. When it becomes optically-thin gamma-ray burst, but a blackbody, not Band spectrum!
- Shemi & Piran (90): add some baryons, energy is converted to kinetic energy



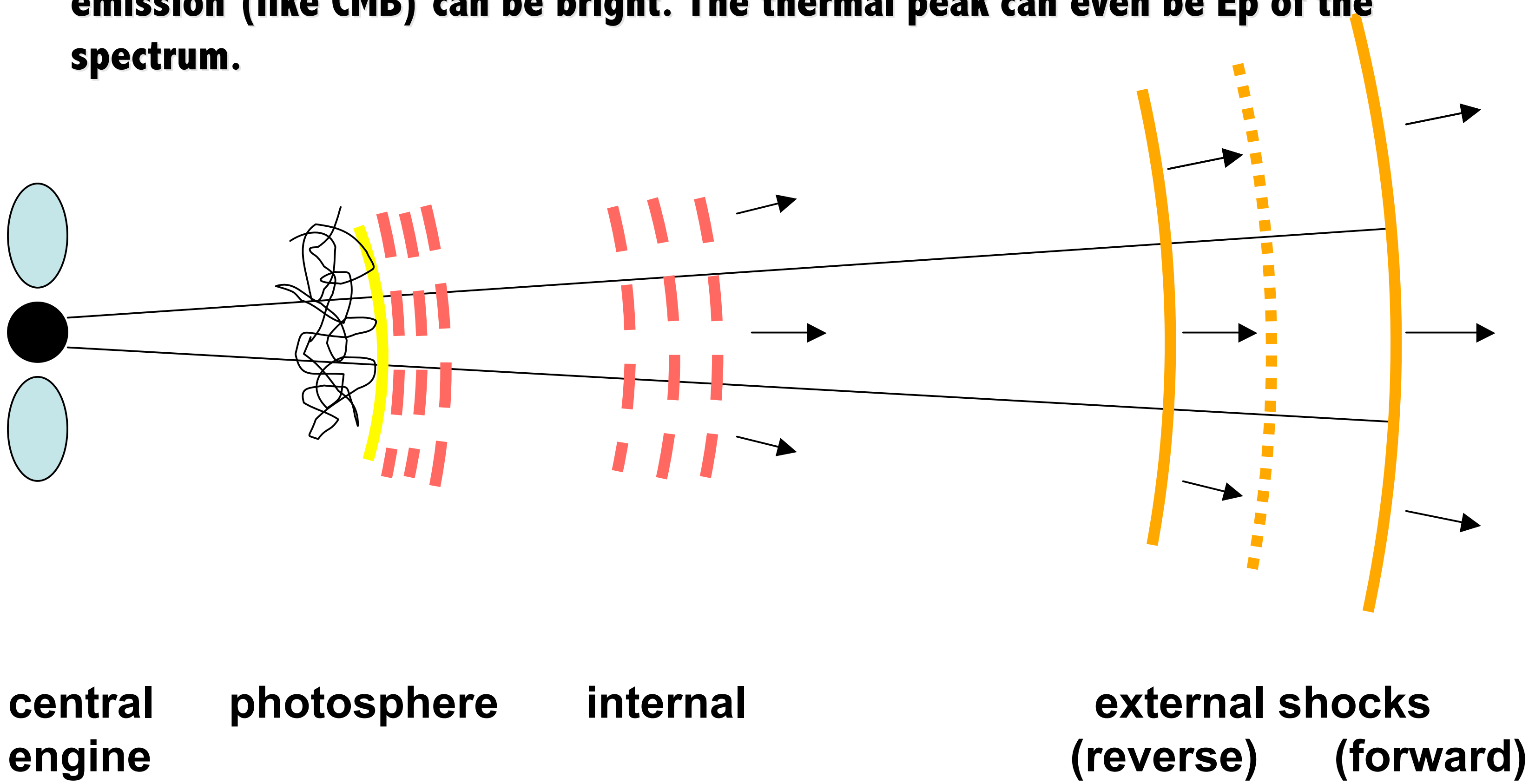
Historical Remark (2)

- Rees & Meszaros (92), Meszaros & Rees (93): the kinetic energy is reconverted back to non-thermal gamma-ray emission in external shock.
- Rees & Meszaros (94), Paczynski & Xu (94): the kinetic energy is reconverted back to non-thermal gamma-ray emission in internal shocks.

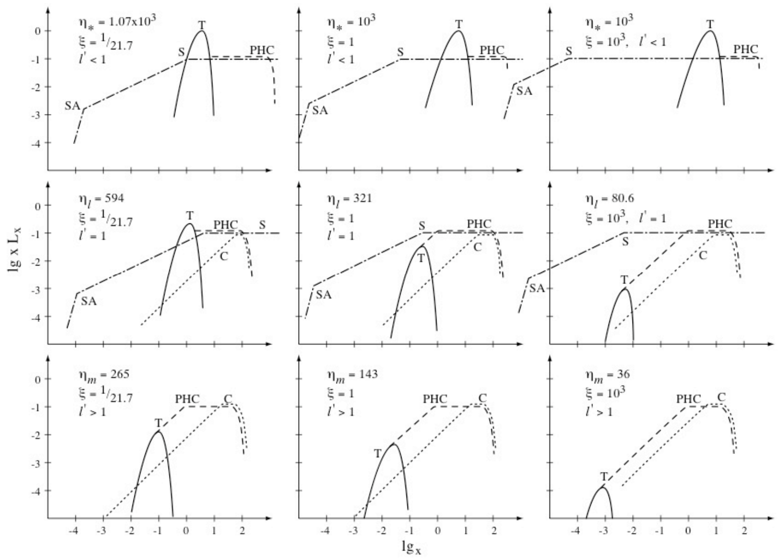


Historical Remark (3)

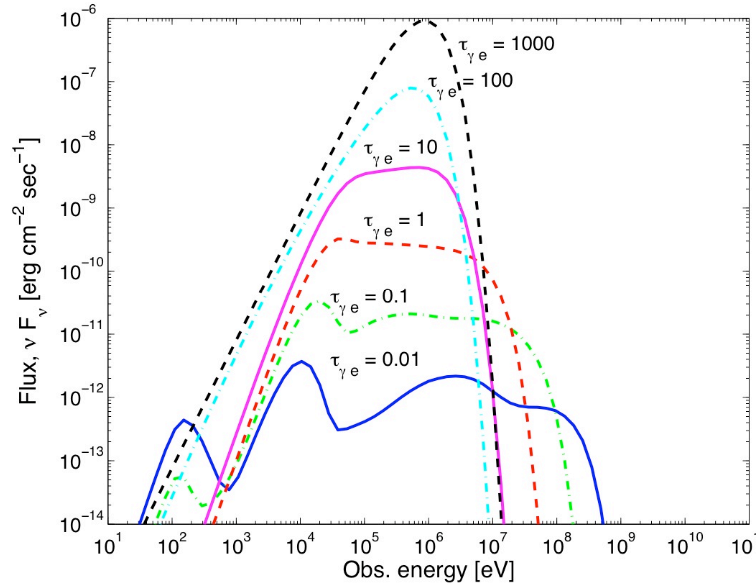
- Meszaros & Rees (00), Meszaros et al. (02), Rees & Meszaros (05), Pe'er et al. (06), Thompson et al. (07), Ioka et al. (07), Pe'er (08):
the observed GRB emission could be superposition of the photosphere emission (may be Comptonized) and that from the internal shocks. The photosphere emission (like CMB) can be bright. The thermal peak can even be Ep of the spectrum.



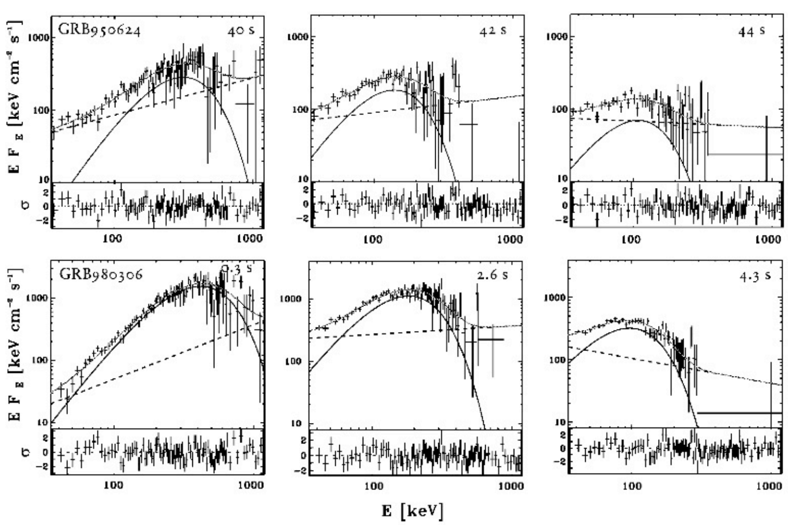
Superposition spectra?



Meszaros & Rees (00)



Pe'er, Meszaros, Rees (06)

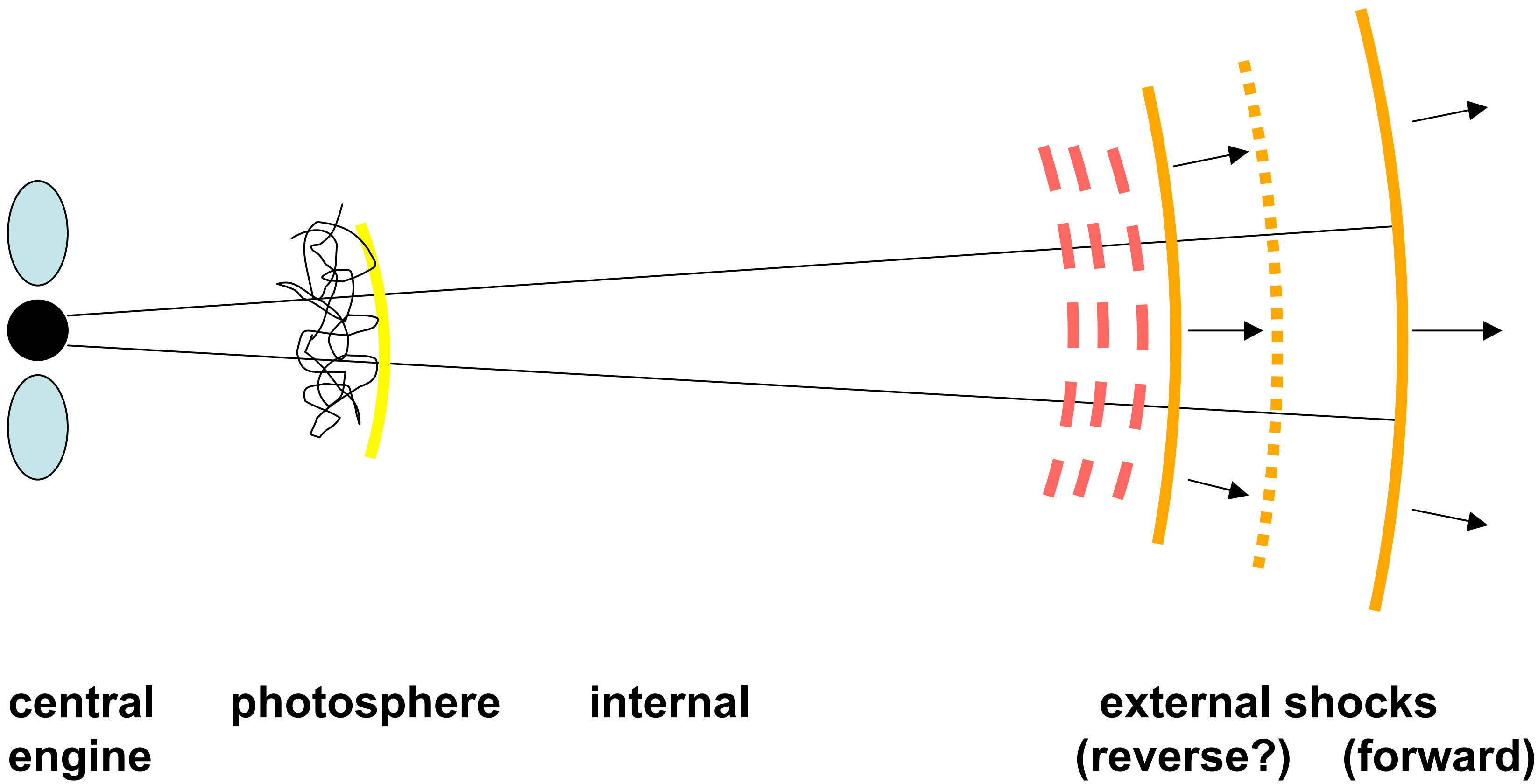


Ryde 05

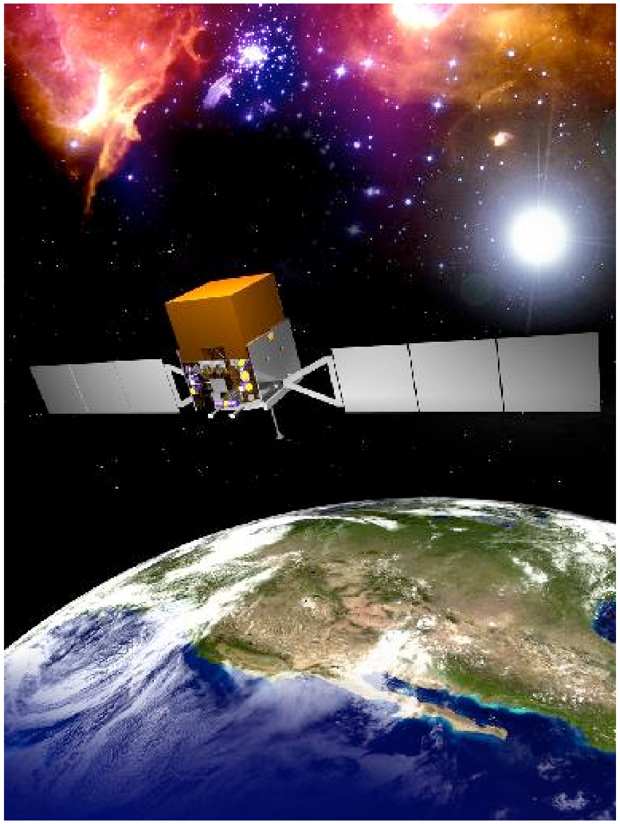
Alternative view:

Magnetic dissipation in a Poynting-flux dominated flow

(Usov 92; Thompson 94 … Lyutikov & Blandford 03)



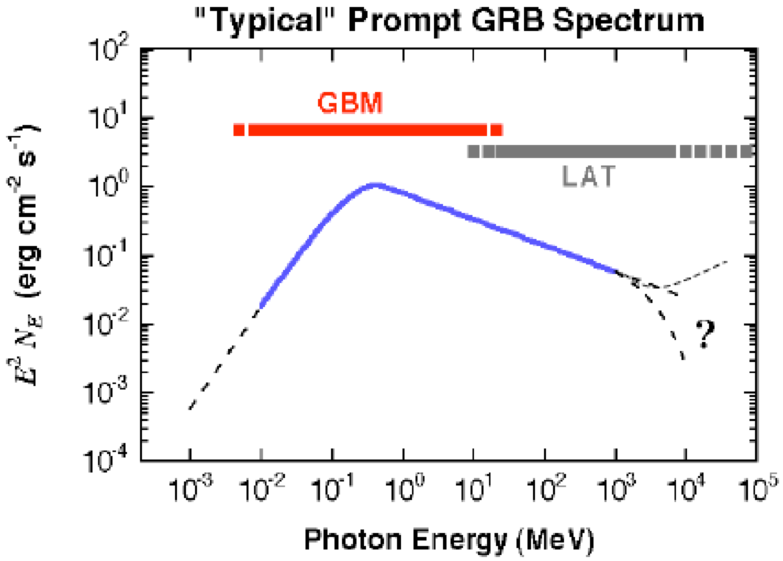
Fermi Revolution:
High energy prompt emission/afterglow



Constrain LIV
Extra spectral component
Minimum Γ??
……

Constrain GRB ejecta composition

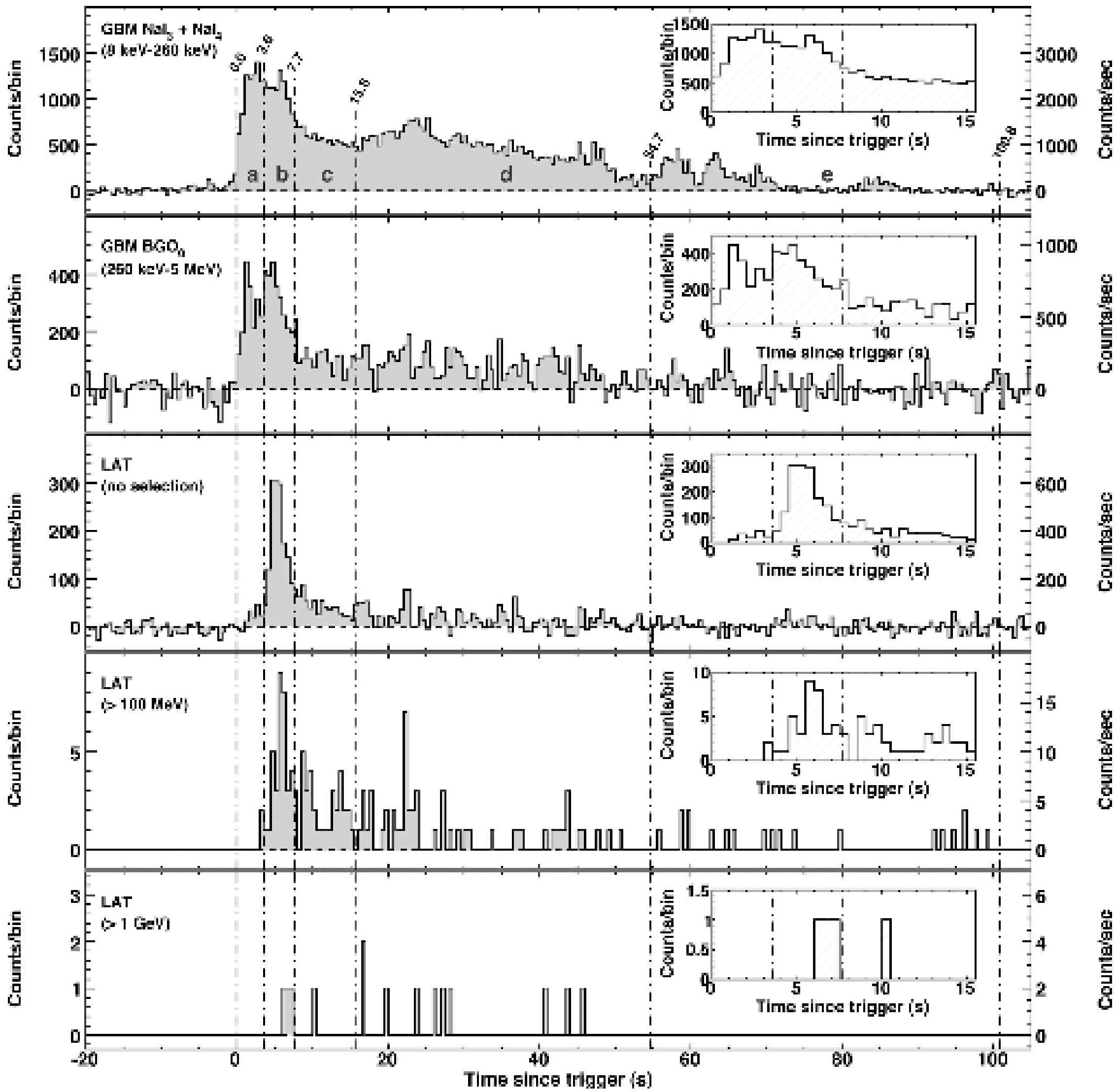
Launched on June 11th,

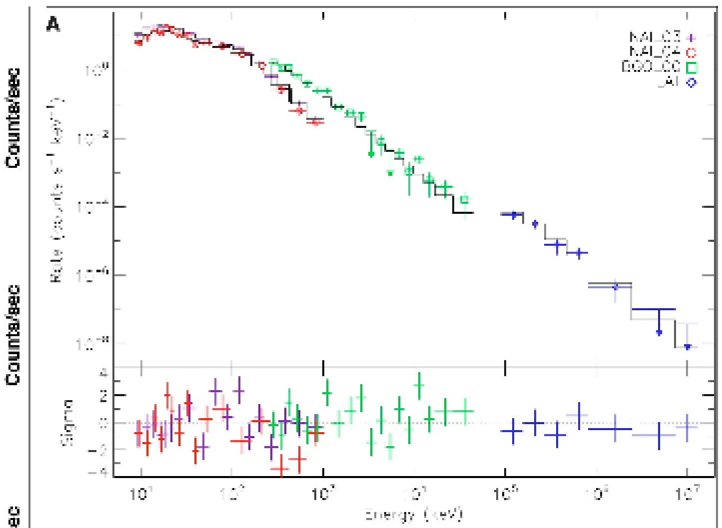


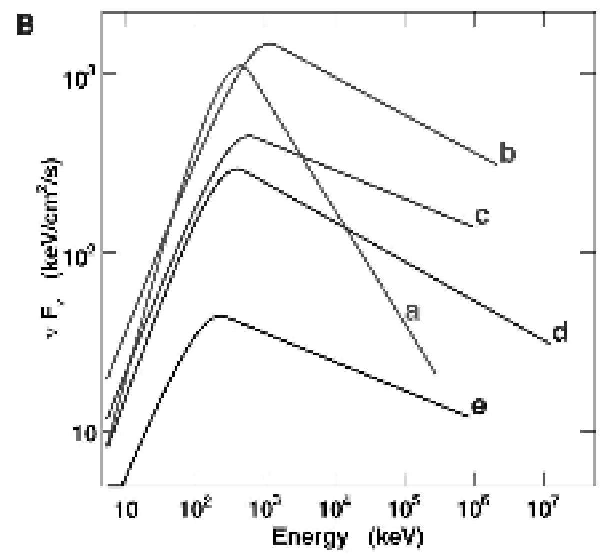
GRB 080916C

(Abdo et al. 2009, Science)

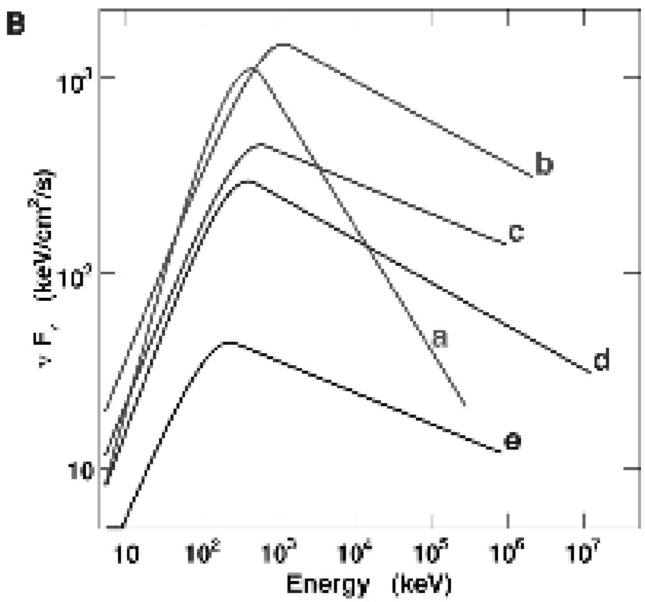
$z = 4.35 \pm 0.15$







What do we learn from GRB 080916C?



Featureless Band-function covering 6 orders of magnitude

Not a surprise? A surprise?

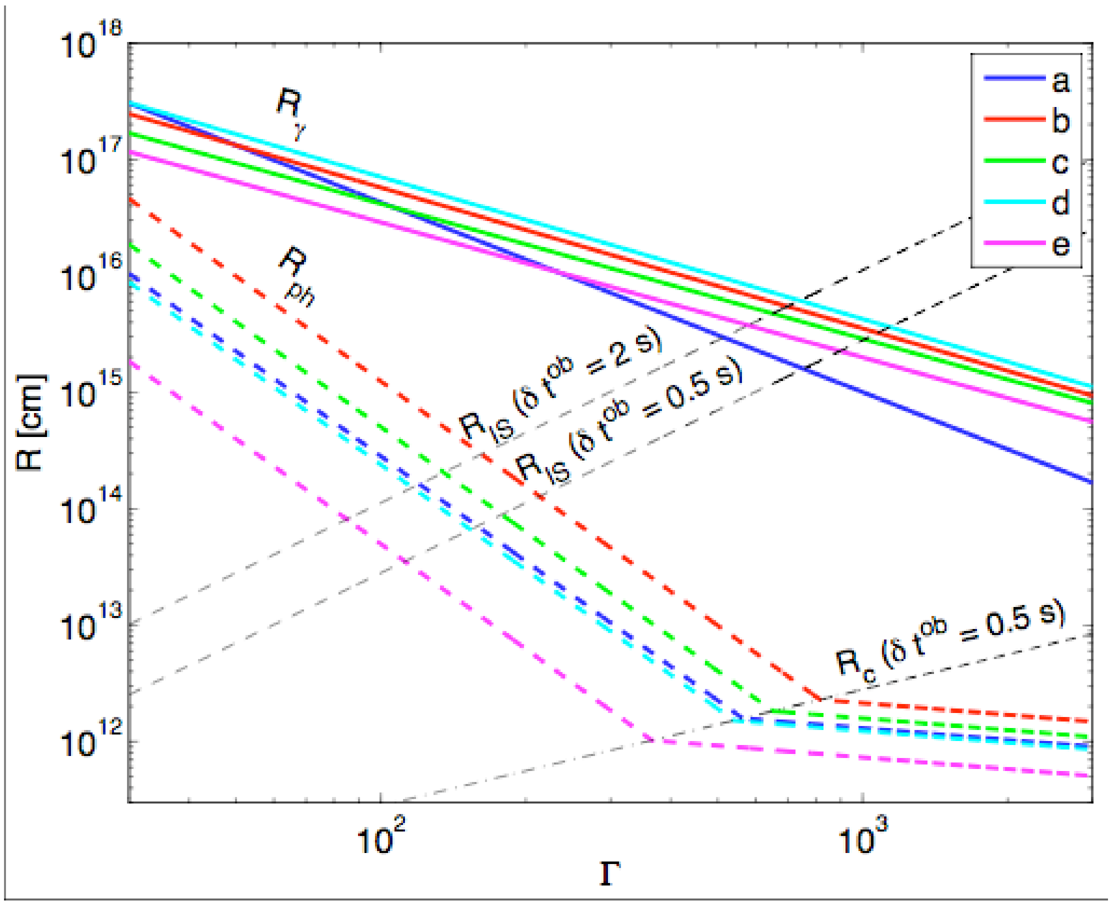
Three features are missing:

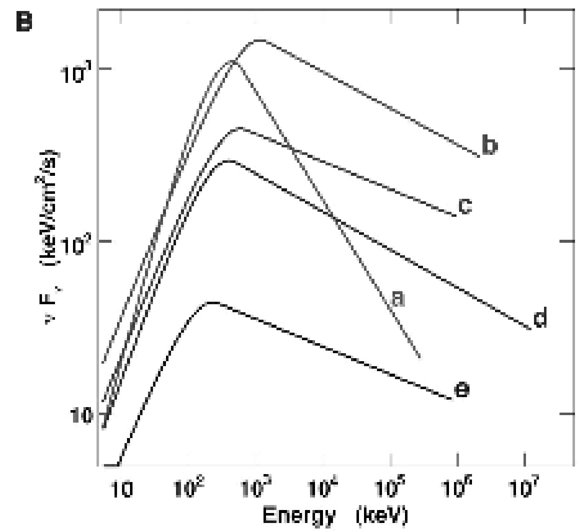
- **No pair cutoff observed**
- **No SSC component detected**
- **Lack of thermal component**

Time bin & Range (s)	A (γ cm^{-2} s^{-1} keV^{-1})	α	β	E_{peak} (keV)	Flux 50-300 keV (γ cm^{-2} s^{-1})	Flux 100 MeV-10 GeV (γ cm^{-2} s^{-1})
a: 0.004 to 3.58	$(55 \pm 2) \times 10^{-3}$	-0.58 ± 0.04	-2.63 ± 0.12	440 ± 27	6.87 ± 0.12	$(2.5 \pm 1.6) \times 10^{-4}$
b: 3.58 to 7.68	$(35 \pm 1) \times 10^{-3}$	-1.02 ± 0.02	-2.21 ± 0.03	1170 ± 140	5.63 ± 0.09	$(4.8 \pm 0.6) \times 10^{-3}$
c: 7.68 to 15.87	$(21 \pm 1) \times 10^{-3}$	-1.02 ± 0.04	-2.16 ± 0.03	590 ± 80	2.98 ± 0.06	$(1.7 \pm 0.2) \times 10^{-3}$
d: 15.87 to 54.78	$(19.4 \pm 0.7) \times 10^{-3}$	-0.92 ± 0.03	-2.22 ± 0.02	400 ± 26	2.44 ± 0.03	$(7.1 \pm 0.9) \times 10^{-4}$
e: 54.78 to 100.86	$(5.2 \pm 0.9) \times 10^{-3}$	-1.05 ± 0.10	-2.16 ± 0.05	230 ± 57	0.54 ± 0.02	$(1.5 \pm 0.4) \times 10^{-4}$

Abdo et al (2009)

GRB 080916C: Radius constraints
(Zhang & Pe'er 09)



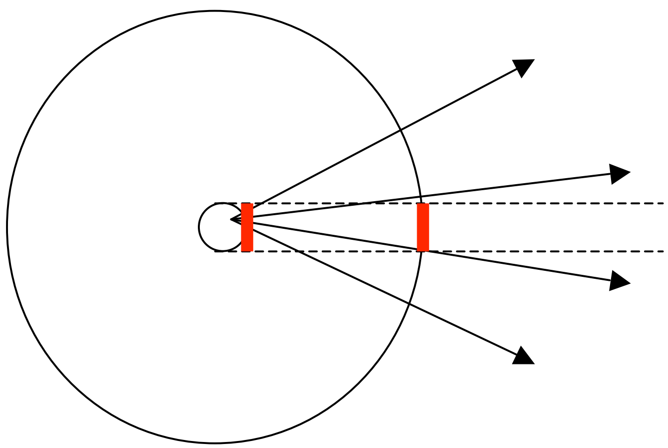


$$\tau_{\gamma\gamma}(E) = \frac{C(\beta)\sigma_T d_z^2 f_0}{-1-\beta}\left(\frac{E}{m_e^2 c^4}\right)^{-1-\beta}\frac{1}{R_\gamma^2}\left(\frac{\Gamma}{1+z}\right)^{2+2\beta}$$

$$f_0 = A\cdot\Delta T\left[\frac{E_p(\alpha-\beta)}{(2+\alpha)}\right]^{\alpha-\beta}\exp(\beta-\alpha)(100\ \mathrm{keV})^{-\alpha}$$

Emission must come from a large radius far away from the photosphere.

Expected photosphere emission from a fireball



Piran et al. 93
Meszaros et al. 93

$\Gamma \propto R \quad T' \propto R^{-1}$

$T = \Gamma T' \propto R R^{-1} = T_0$

$A \propto R^2 \Gamma^{-2} \propto R^2 R^{-2} = A_0$

$L_{th} \sim L_w > L_\gamma$

$$L_{th} = \begin{cases} L_w, & \eta > \eta_*,\ R_{ph} < R_c, \\ L_w(\eta/\eta_*)^{8/3}, & \eta < \eta_*,\ R_{ph} > R_c. \end{cases}$$

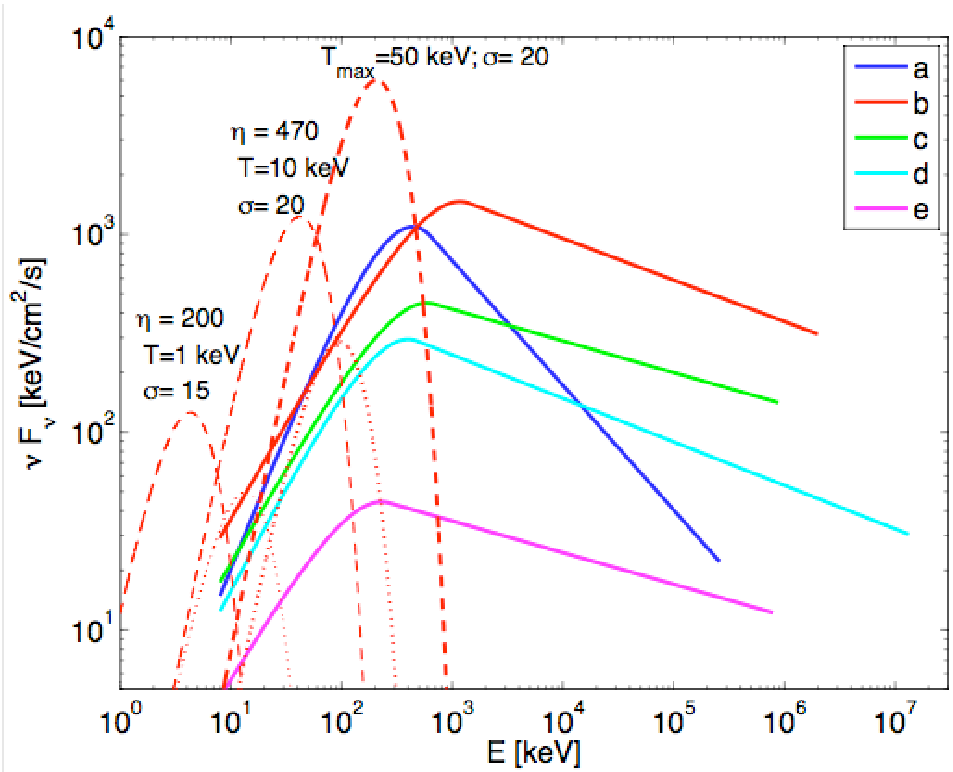
$$\eta_* = (L_w \sigma_T / 8\pi m_p c^3 R_0)^{1/4}$$

Meszaros & Rees (00)

Meszaros, Ramirez-Ruiz, Rees & Zhang (02)

Expected photosphere emission from a fireball

(Zhang & Pe'er 09)



-The thermal residual emission from the fireball is TOO bright to be consistent with the data

- In order to hide the thermal component, a significant amount of ejecta energy is initially not in the thermal form

- The flow has to be Poynting-flux dominated at the central engine!

Sigma: ratio between Poynting flux and baryonic flux:
$\sigma = L_p/L_b$

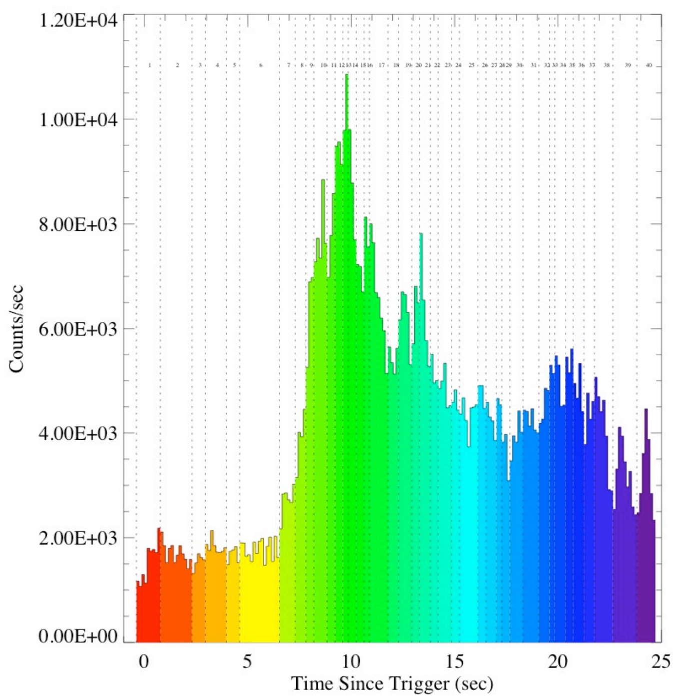
σ At least ~ 20, 15 for GRB 080916C

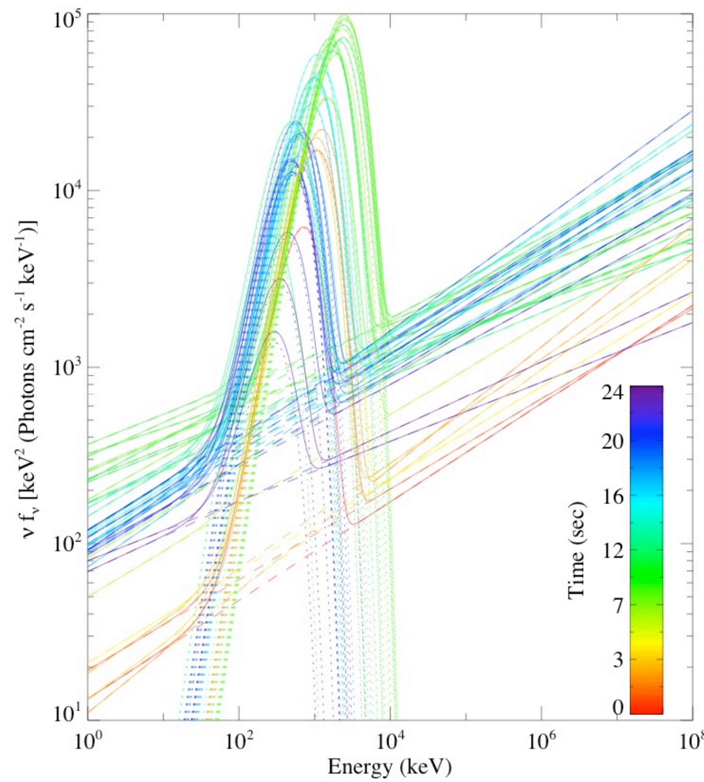
Kill Three Birds with One Stone

- Invoking a Poynting flux dominated flow can explain the lack of the three expected features
  - Non-detection of the pair cutoff feature is consistent with a large energy dissipation radius
  - Non-detection of the SSC feature is naturally expected, since in a Poynting flux dominated flow, the SSC power is expected to be much less that the synchrotron power
  - Non-detection of the photosphere thermal component is consistent with the picture, since most energy can be retained in the form of Poynting flux energy rather than thermal energy
- Also consistent with
  - Numerical modeling
  - Polarization observation of early optical afterglow of GRB 090102 (Steele et al.)

New Surprise: Thermal emission in GRB 090902B!

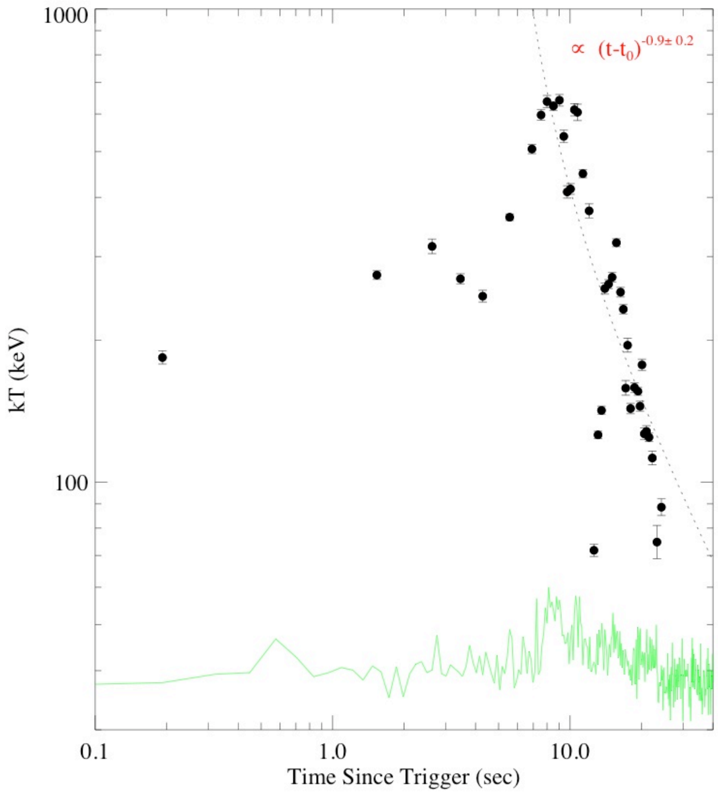
Ryde et al. (2009); Pe'er et al. (2009) in preparation

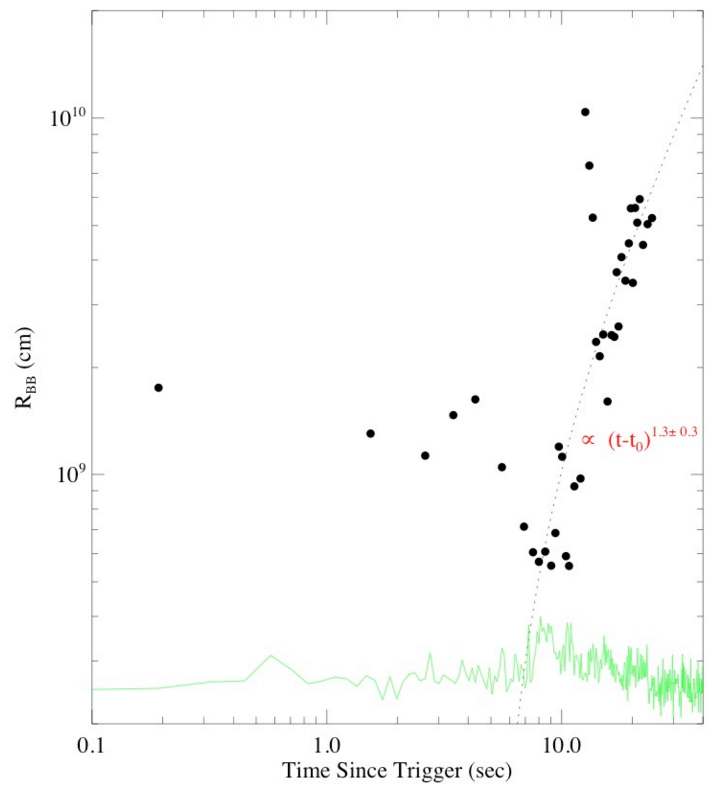




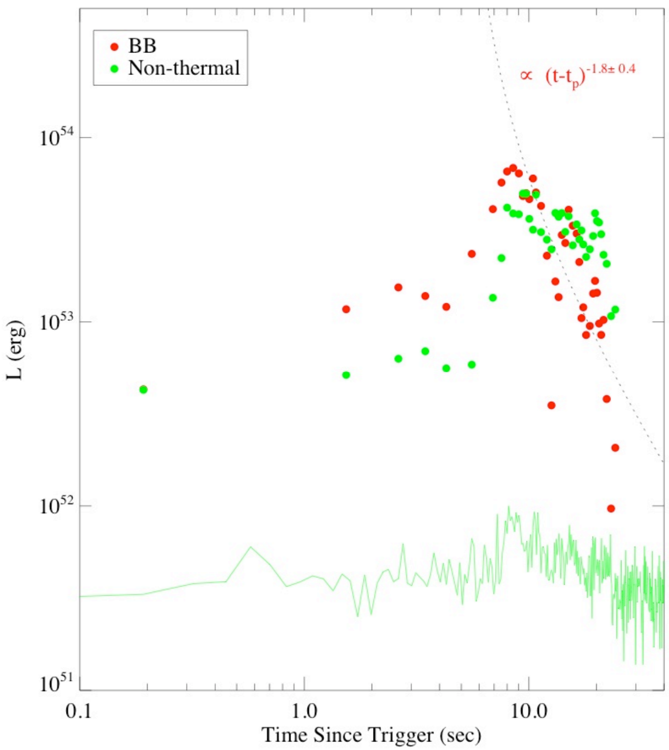
This is a Paczynski-Goodman "fireball"!

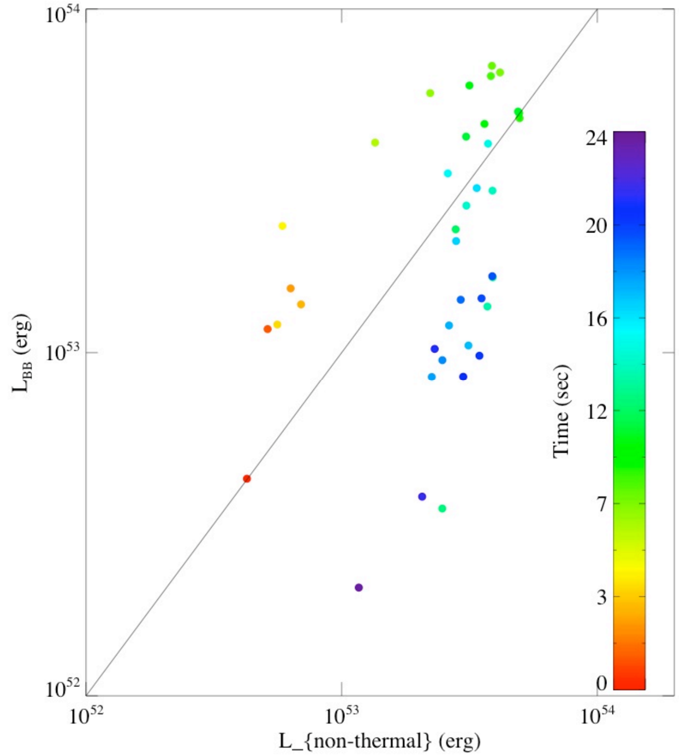
GRB 090902B - cont.





GRB 090902B - cont.

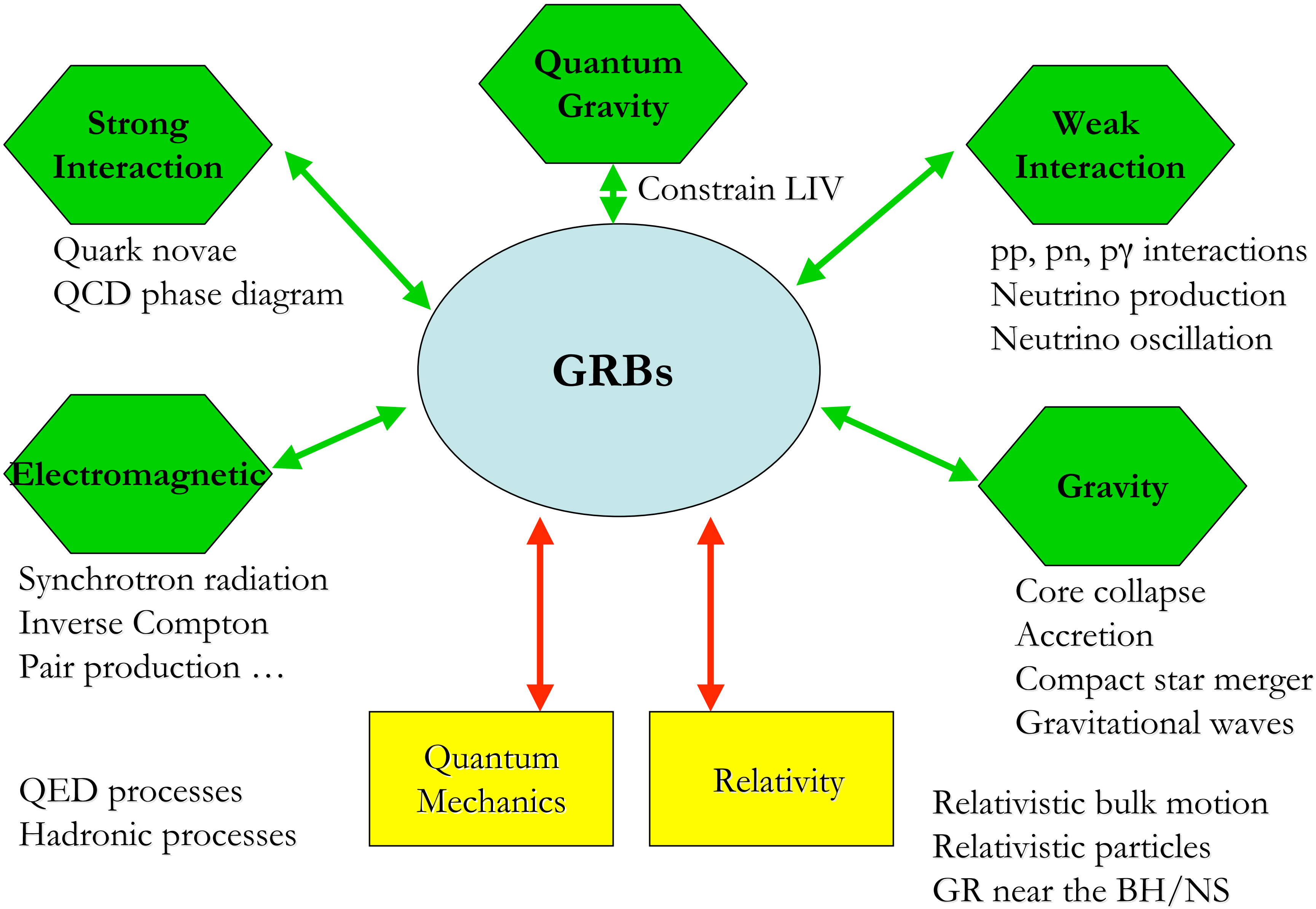




Inferences from the Fermi observations

- The broad-band Fermi GBM/LAT data can be used to constrain GRB jet composition.
- GRB composition is diverse. Magnetization parameter σ may vary in a wide range.
- At least GRB 080916C is very likely Poynting flux dominated at the central engine; at least GRB 090902B is very likely a hot fireball.

GRBs & Physics

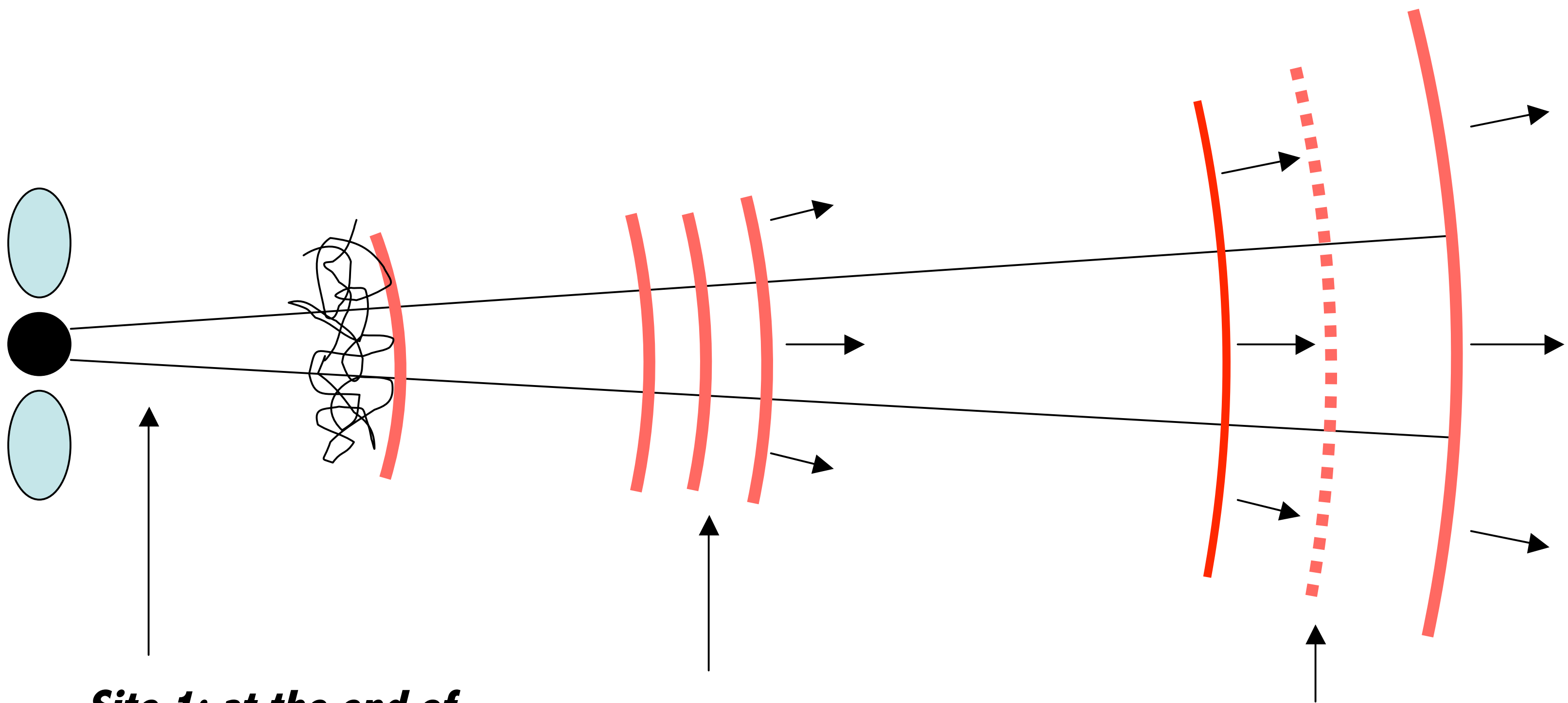


Future milestones?

- Gamma-ray/X-ray polarization measurements?
- High energy neutrino detection?
- Connection to ultra high energy cosmic rays?
- Gravitational wave detection?

High energy neutrinos from GRBs

GRBs as HE neutrino sources



Site 1: at the end of the acceleration phase (in some cases)

***pn* process (GeV)**

Bahcall & Meszaros 00

Site 2: in internal shocks

***pγ* process (0.1-1 PeV)**

Waxman & Bahcall 97

Guetta et al. 04

Gupta & Zhang 06

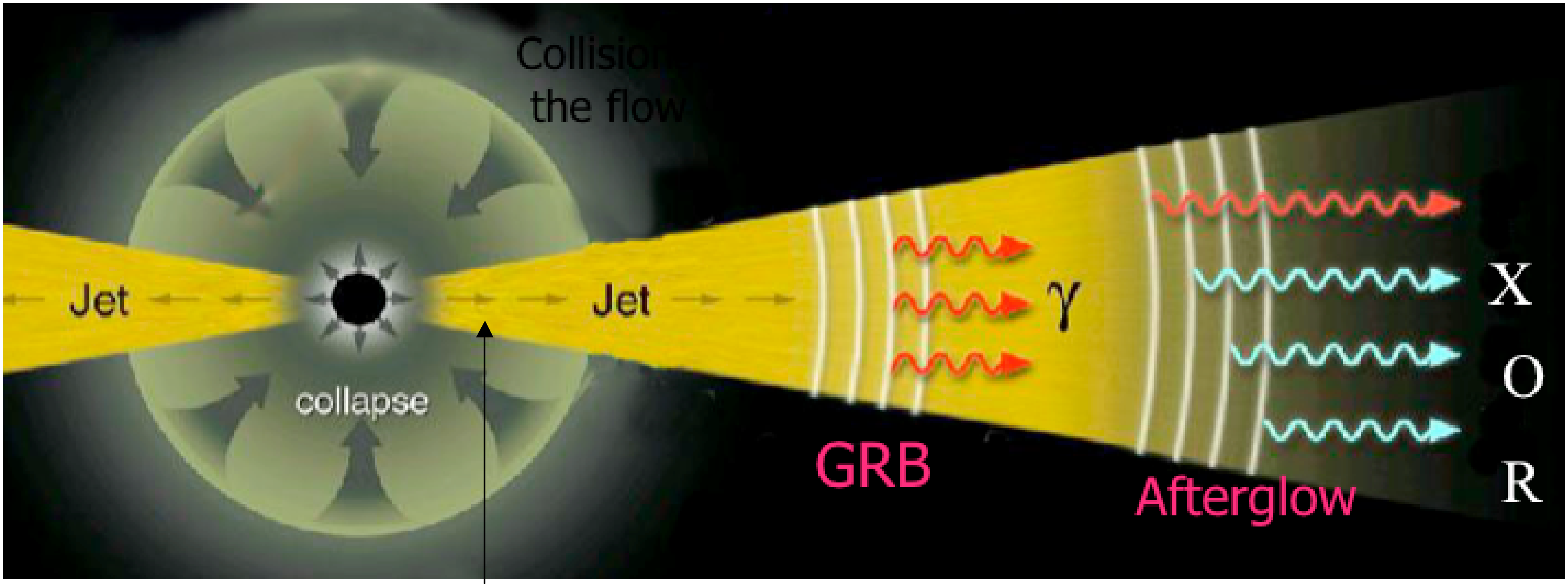
Site 3: in external shocks (both forward and reverse)

***pγ* process (0.1-1 EeV)**

Waxman & Bahcall 00, Dai & Lu 01

(~ 1 PeV) Fan, Zhang & Wei 05

Another site for long GRBs



Site 4. Internal shocks inside the star
(this component is also valid for failed GRBs)
***pγ* process; *pp* process (TeV)**

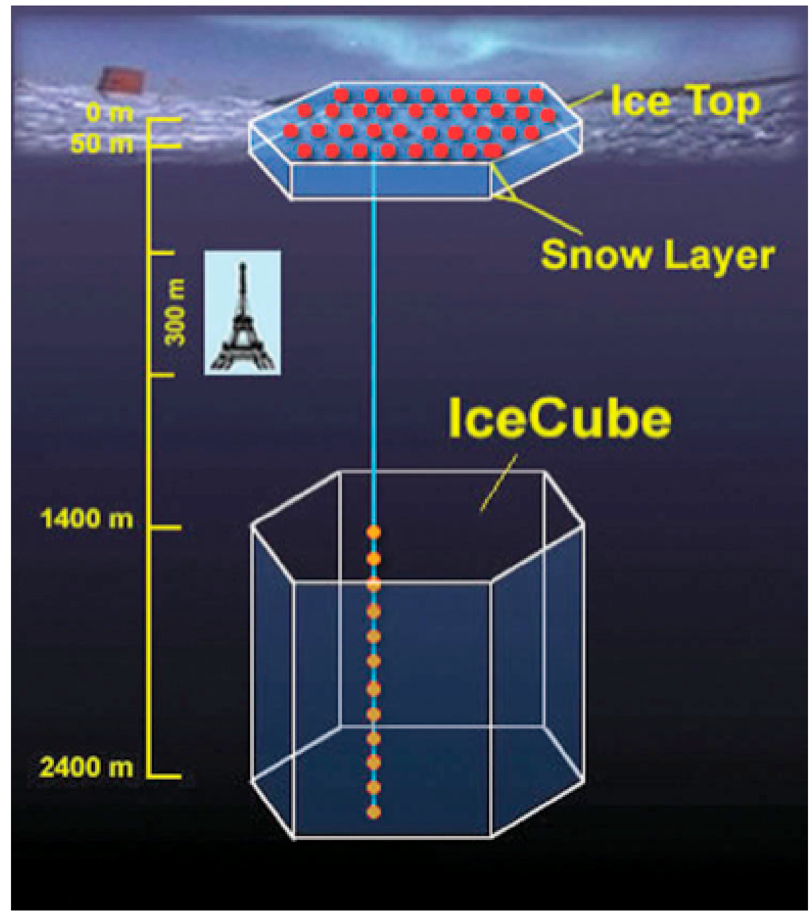
Meszaros & Waxman 01
Razzaque et al. 03,04
Dermer & Atoyan 03

Issue: Are GRBs baryonic & magnetic?

- If GRBs are mainly baryonic, hydro-shocks exist and the above-mentioned neutrino signals should be expected
- However, if GRBs are mainly magnetic - i.e. Poynting flux dominated, then the expected neutrino signals should be lower.
- Fermi observations show the existence of both types - maybe GRBs have a range of composition.

Implications

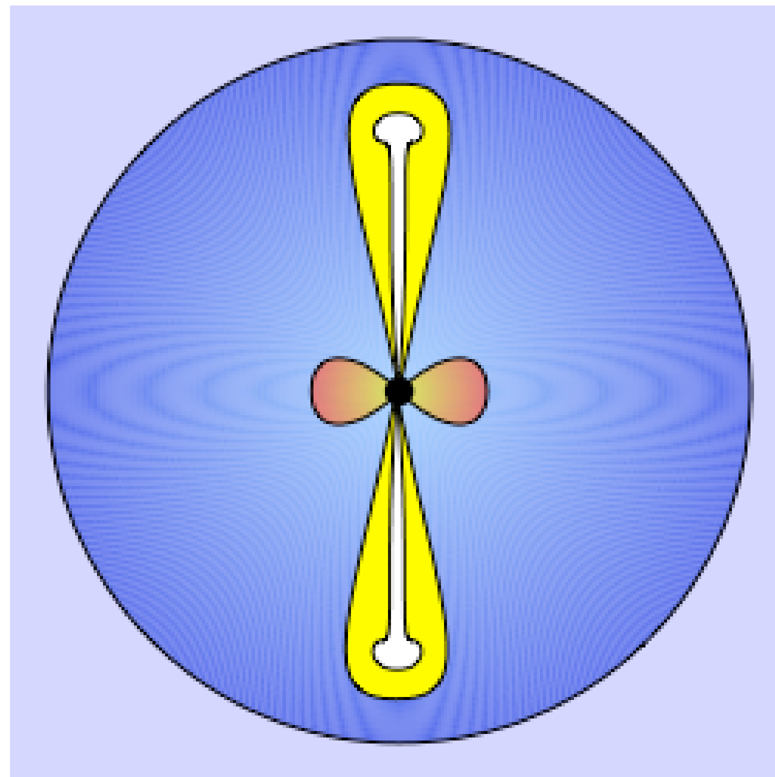
• Optimistically, IceCube will soon detect HE neutrino signals from individual bursts and the GRB diffuse neutrino background.
• Pessimistically, the real HE neutrino flux level from GRBs is much lower
• If no detections, tight constraints would suggest the magnetic origin of GRBs



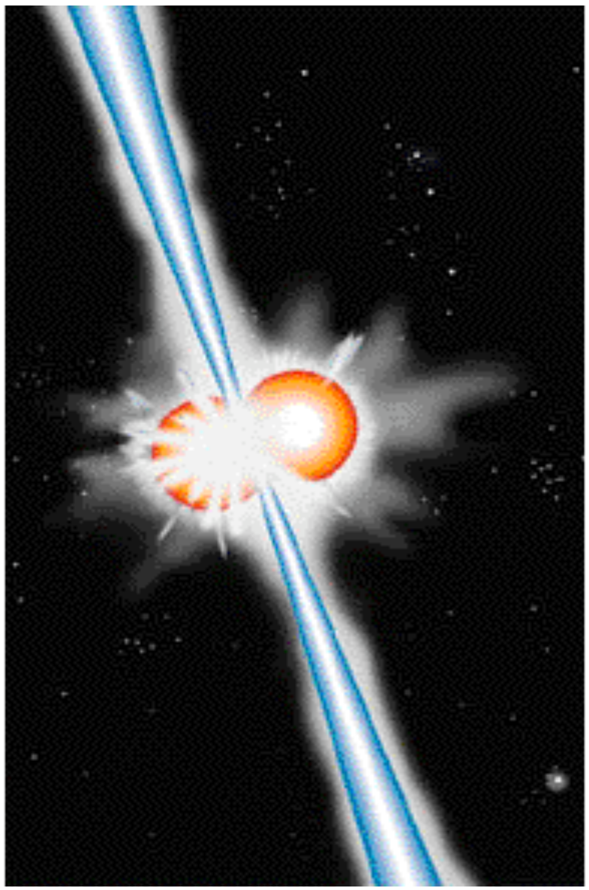
Neutrino oscillation from collapsar jets

Sahu & Zhang (2009)

• For “choked” GRBs, TeV neutrinos can be produced by interaction of the choked jet and the star;
• The He envelope is the right size for neutrino oscillation to occur inside the star (for certain oscillation parameters);
• The final arrival species ratio is modified: 1:1.3:1.3 or 1:1.1:1.1 (instead of 1:1:1)



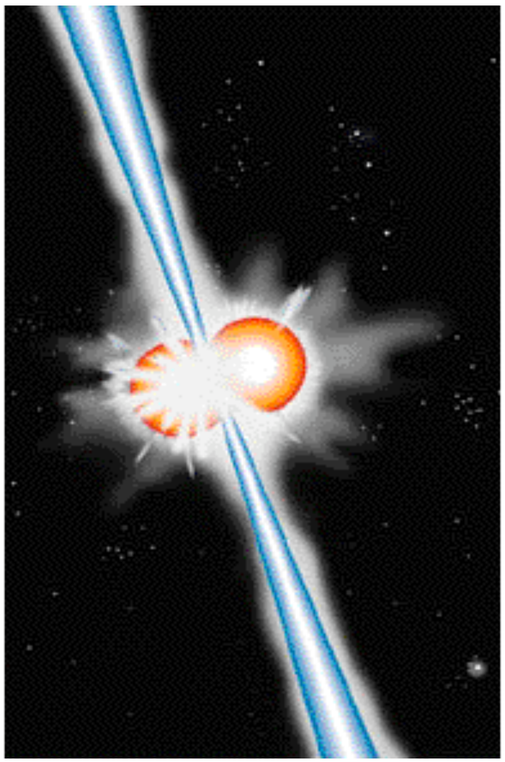
Gravitational waves from GRBs?

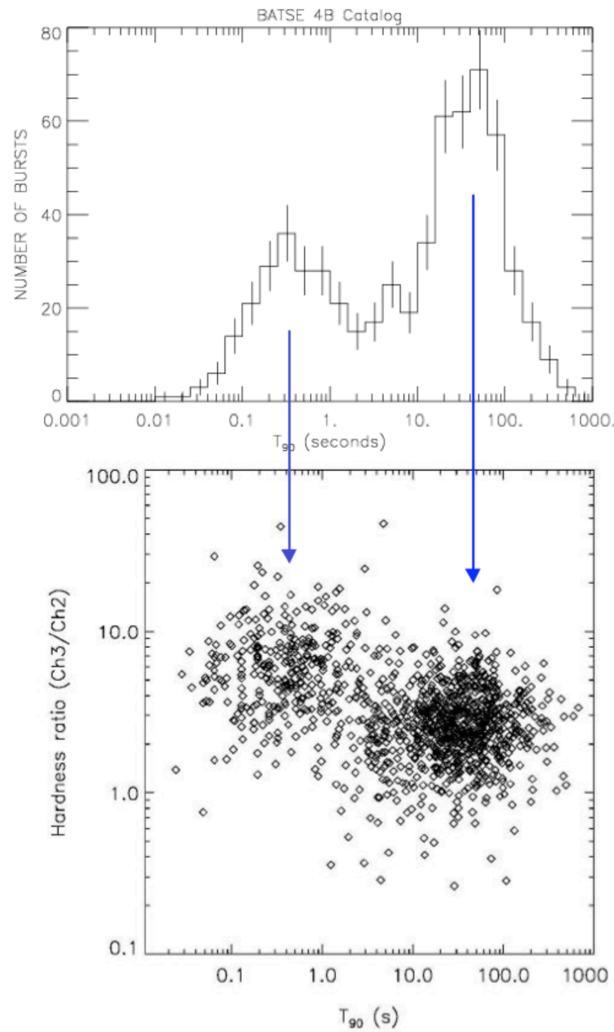


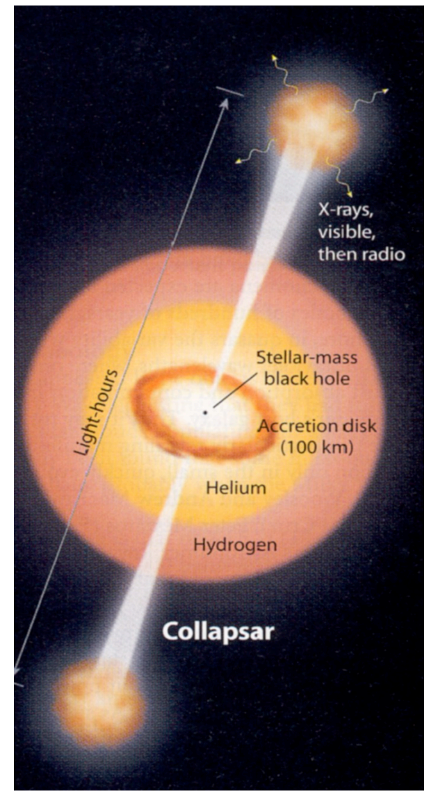
NS - NS mergers

NS - BH mergers

“Long” vs. “Short” - dual meanings







Popular quotes in GRB conferences & literature:

- This long GRB may be “short”
- That short GRB may be “long”
- This is a long “short” (or “long” short) GRB
- That is a short “long” (or “short” long) GRB

Phenomenological:

Long vs. Short

Physical:

Type II (massive star GRBs)
vs. Type I (compact star GRBs)

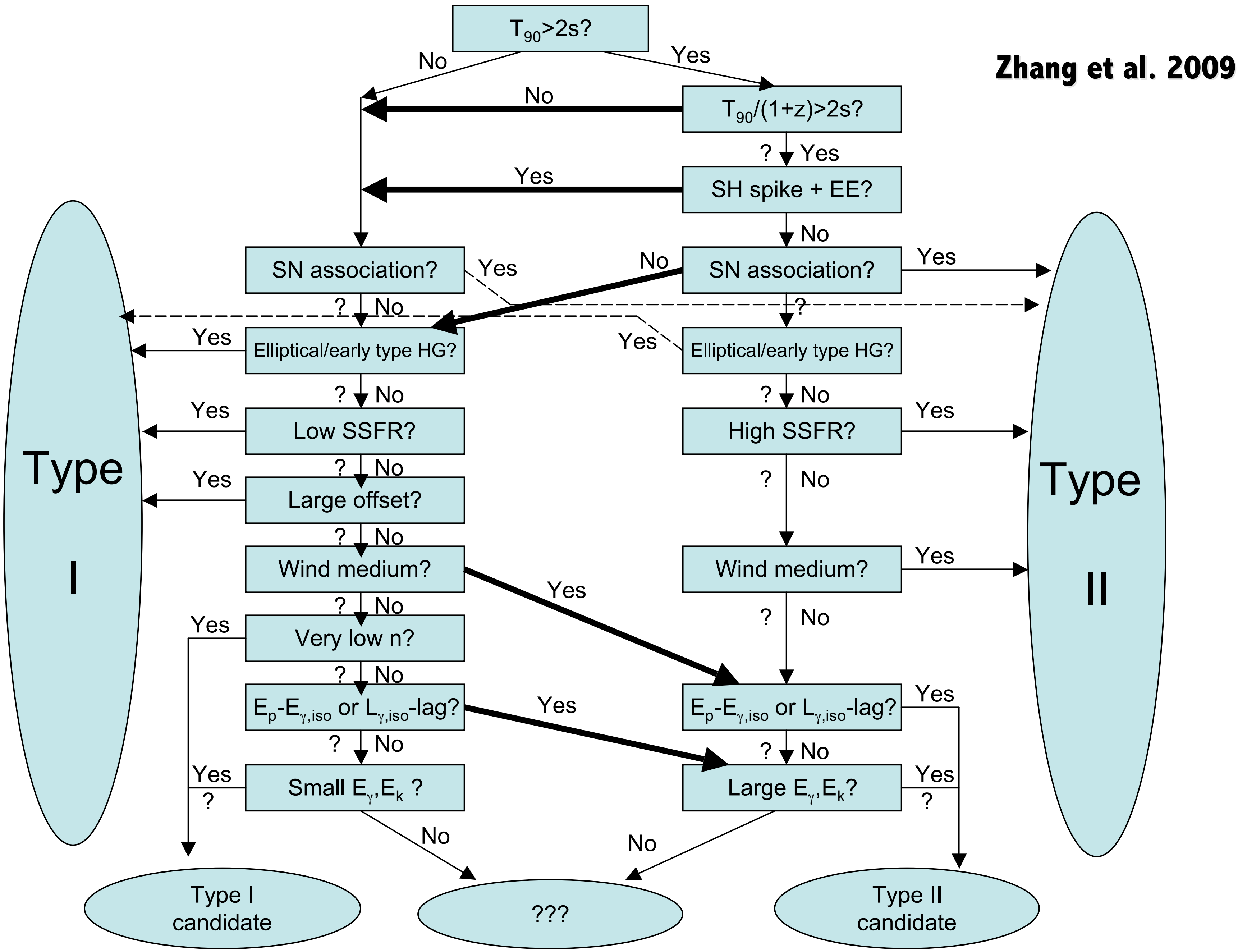
How to tell the physical category from the observations?

Multiple observational criteria needed!

TABLE 2
OBSERVATIONAL CRITERIA FOR PHYSICALLY CLASSIFYING GRBS.

Criterion	Type I	Type II	Issues
Duration	Usually short, but can have extended emission.	Long without short/hard spike, can be shorter than 1s in rest frame.	No clear separation line.
Spectrum	Usually hard (soft tail)	Usually soft	Large dispersion
Spectral Lag	Usually short	Usually long, can be short.	Related to variability time scale
$E_{\gamma,iso}$	Low (on average)	High (on average)	Wide dstribution in both
$E_p - E_{\gamma,iso}$	Usually off the track.	Usually on the track.	Some Type II off the track.
$L^p_{\gamma,iso}$–lag	Usually off the track.	Usually on the track.	Some Type II off the track.
SN association	No.	**Yes.**	Some Type II may have no association.
Medium type	Low-n ISM.	**Wind** or High-n ISM.	Large scatter of n distribution.
$E_{K,iso}$	Low (on average)	High (on average)	Large dispersion
Jet angle	Wide (on average)	Narrow (on average)	Difficult to identify jet breaks
E_γ and E_K	Low (on average)	High (on average)	Type I BZ model $\sim$ Type II.
Host galaxy type	**Elliptical, early** and late	Late	Deep spectroscopy needed.
SSFR	**Low** or high	High (exception GRB 070125)	
Offset	Outskirt or outside	Well inside	How to claim association if outside?
z-distribution	Low average z	High average z	
L-function	?	Broken power law, 2-component	

Zhang et al. (2009)



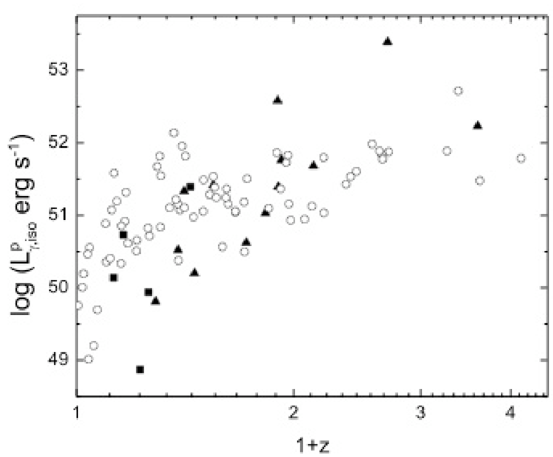
Zhang et al. 2009
T90>2s?
No
Yes
T90/(1+z)>2s?
No
? Yes
SH spike + EE?
Yes
No
SN association?
Yes
No
SN association?
Yes
? No
?
Elliptical/early type HG?
Yes
Yes
Elliptical/early type HG?
? No
? No
Low SSFR?
Yes
High SSFR?
Yes
? No
Large offset?
Yes
? No
? No
Wind medium?
Yes
Wind medium?
Yes
? No
? No
Very low n?
Yes
? No
Ep-Eγ,iso or Lγ,iso-lag?
Yes
Ep-Eγ,iso or Lγ,iso-lag?
Yes
? No
? No
Small Eγ,Ek ?
Yes ?
Large Eγ,Ek?
Yes ?
No
No
Type I
Type II
Type I candidate
???
Type II candidate

Compact Star Merger Model: Swift/BATSE do not square!

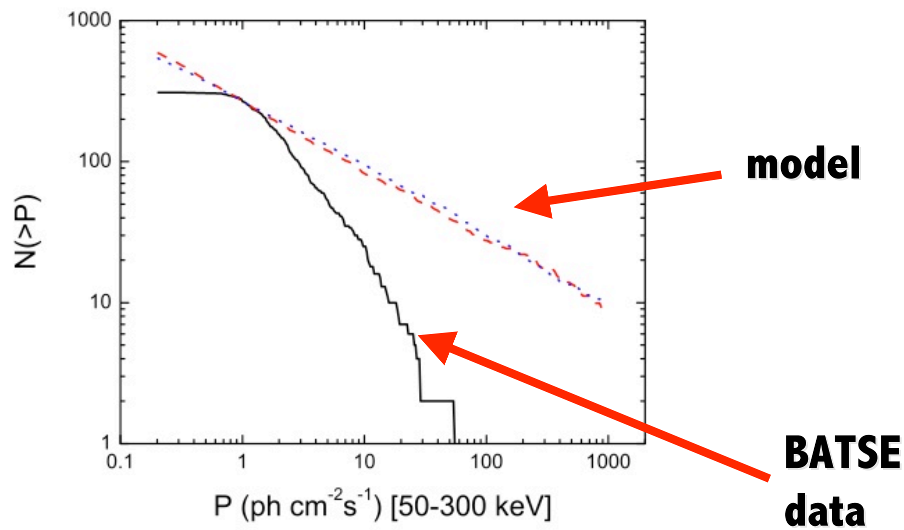
Virgili, Zhang, O'Brien & Troja (2009)

Monte Carlo simulation:

1. **Input: luminosity function & z - distribution (star formation + merger delay)**
2. **Use observed L-z to constrain LF and z - distribution**
3. **Use the same model try to reproduce the BATSE Log N - Log P**



L - z



Log N - Log P

Most short GRBs need to follow star formation - consistent with star forming hosts

Implications

• Optimistically, Advanced LIGO will start to detect GW signals due to NS-NS (NS-BH) mergers in a few years
• Pessimistically, the majority of short GRBs are not associated with these mergers, the GW signals may not be strong

Conclusions

- We have learned a lot more about GRBs in recent years (Swift & Fermi)
- New breakthroughs are expected in the years to come (high energy neutrinos and gravitational waves)
- This is a dynamical field. New surprises always accompany!